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A simple method has been developed to model crossflow separation for inviscid (Euler type) computations by suppressing the crossflow velocity near the body surface. The method has been validated for a tangent-ogive-cylinder body of circular cross-section and shown to be useful at supersonic speeds at low to intermediate angles of incidence ($M < 5$, $\alpha < 20$ deg). At low Mach numbers ($M < 3$) the method offers a significant improvement in the inviscid leeside surface pressure distributions and also yields improved predictions of aerodynamic coefficients. In this report the algorithm for a tangent-ogive-cylinder body is described and comparisons of numerical and experimental data are presented.

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LEESIDE CROSSFLOW MODELING IN EULER SPACE-MARCHING COMPUTATIONS

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STRATEGIC SYSTEMS DEPARTMENT

NOVEMBER 1986

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FOREWORD

This report presents a method for leeside crossflow separation modeling in Euler space-marching computations. Description of the method and validation comparisons for a tangent-ogive body at supersonic speeds at low to intermediate angles of incidence are included.

This work was supported by Aerodynamics and Structures Technology funding under the direction of Dr. Frank G. Moore. Contribution of Jack Hase (G-23) in performing a number of validation computations is greatfully acknowledged.

Carl W. Larson

CARL W. LARSON
By direction

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (CONT.)

INTRODUCTION

The Euler equations provide an efficient means for supersonic flow computations and are widely used in aircraft and missile aerodynamic performance studies. The viscous effects in such studies are often of secondary importance and skin friction can be computed separately and added to inviscid results. However, in cases involving slender bodies or highly swept wings at incidence, the leeside flow structure is strongly influenced by the viscous effects. Such effects need to be included in the main computational process.

While the Navier-Stokes equations provide a rigorous approach to the viscous flow problem, the solutions available at present are too costly for many engineering-type aerodynamic computations. Accordingly, interest in using and developing viscous modeling for Euler equations persists.

Of particular interest at present is the leeside region of slender bodies at incidence. The flow structure in such a region is strongly influenced by crossflow separation and is dominated partly by the crossflow shock and partly by the viscous boundary layer at the surface. While the crossflow shock and its effects are generally accounted for by the Euler equations, the viscous boundary layer effects need to be included within the Euler computation through special modeling. One method is to prescribe the crossflow separation point using an experimental data base and then numerically simulate such separation by the application of additional constraints.[1,2] From the limited data available, this seems to bring the overall leeside flow structure into better agreement with experiment. However, this method requires a prior knowledge of the location of the separation point and erratic surface pressure values often occur near the prescribed separation.

To avoid the above difficulties a different approach is described in the present report. Instead of being rigidly prescribed, separation is allowed to take place in conformance to the leeside circulation level, which is augmented by suppressing the crossflow velocity near the surface. A simple method for such augmentation has been developed and is shown to be valid over a range of Mach numbers and angles of incidence. In this report the algorithm for a tangent-ogive-cylinder body is described and comparisons of numerical and experimental data of the surface pressure distributions, local flow angularities and also of aerodynamic force coefficients are presented.

METHOD OF APPROACH

In an inviscid computation, the crossflow shock generally occurs farther leeward than is experimentally observed. It is accompanied by a sharp pressure rise which is not found experimentally. In an equivalent viscous case the shock interacts with the boundary layer and is diffused and weakened at the surface. The location of the shock is altered by this interaction, as well as by the crossflow circulation that is generated by the boundary layer. To bring the leeside flow structure in closer agreement with the viscous case, modeling of the boundary layer is necessary. In the present effort this was undertaken by utilizing available experimental data and generating numerical data with the NSWC SWINT code (Ref. 3). The flow conditions of primary interest were low-to-intermediate supersonic Mach numbers ($M < 5$) and angles of attack of up to about 20 degrees. Model geometries consisted mostly of sharp-tip tangent-ogive cylinders, approximately ten diameters long. The boundary layers of the experimental data were in the turbulent range.

Initially, a no-slip surface boundary was applied in the crossflow direction. This diffused the crossflow shock at the surface, but also raised the pressure on the windward side of the model. To correct this, the no-slip type boundary was replaced by crossflow velocity clipping. Here the crossflow velocity was reduced to ensure that the Mach number of the velocity component in the crossflow plane did not exceed the value M_{CR}. Clipping was applied both on and near the model surface using the constraint

$$M_{CR} = 0.145 \cdot \sqrt{\alpha} \circ (r/b)^2$$

where

b = body radius
r = radial distance
α = body angle of incidence, deg

Clipping does not change static pressure (p) or density (ρ), and thus enthalpy ($h(p, \rho)$) and entropy ($s(p, \rho)$) are also unchanged. The total stagnation enthalpy constraint is satisfied by re-defining the axial velocity component, w, as follows:

$$w = 2(H_0 - h) - u^2 - v^2$$

where
H_0 = total stagnation enthalpy
h = enthalpy
u = radial velocity component
v = circumferential velocity component.

The update changes for application of this algorithm in the NSWC SWINT code are given in the Appendix.

The above algorithm performs well over a range of freestream Mach numbers and angles of incidence, as will be shown later in this report. Freestream Reynolds number is likely to have a significant effect on crossflow separation and leeside surface pressures, particularly in the transitional boundary layer

range at low supersonic Mach numbers (e.g., see Ref. 4). It is not included as a parameter in the present algorithm because of inadequate experimental data for verification. The present algorithm is intended for turbulent, high Reynolds number cases.

VALIDATION

Crossflow velocity clipping has a strong effect on the crossflow velocity profiles, as is illustrated in Fig. 1. In the windward region (ϕ = 60 deg.), the difference between the inviscid and clipped profiles is small. On the leeside, ahead of the inviscid crossflow shock (ϕ = 120 deg.), clipping greatly reduces the crossflow velocity near the model. Farther leeward (ϕ = 160 deg.), clipping produces a vortex which results in an increased region of reversed crossflow velocity.

The effect of crossflow velocity clipping on the surface pressure coefficient is shown in Figs. 2A to 2H. Longitudinal and circumferential comparisons with inviscid calculations and experimental data are included for Mach numbers from 1.98 to 4.5. The longitudinal variations are for the leeside plane ahead of the crossflow shock (for inviscid computations). The circumferential profiles are near the end of the model. The figures show crossflow velocity clipping to be very effective in bringing the inviscid surface pressures closer to experimental results, particularly at lower supersonic speeds ($M < 4.5$). Figure 2A, for example, shows that at $M_\infty = 1.98$, α = 15 deg, the inviscid surface pressure, along the longitudinal plane at ϕ = 105 deg, downstream of the forebody, deviates severely from the experimental results. Suppression of the crossflow velocity brings the computed pressures in much better agreement with experiment. In the circumferential direction (Fig. 2B) the inviscid results indicate an over-expansion and then a strong crossflow shock, while the modified crossflow pressures follow the experimental data more closely. Figures 2C, 2D and 2E, 2F show similar improvements in longitudinal and circumferential pressure profiles for Mach numbers of 2.3 and 2.96. Figures 2G and 2H show that at Mach 4.63 the differences in leeside surface pressures are less severe, but that the present modification method still offers improvement.

Comparison of the model normal force and pitching moment coefficients are shown in Figures 3A to 3D. The effect of crossflow clipping on the integrated surface pressures is also favorable, but less pronounced.

Clipping brings the inviscid results closer to experiment by increasing the circulation and creating a leeside vortex that is similar to one formed by the boundary layer separation and roll-up. Figure 4A to 4D illustrate the computed leeside flow fields with and without clipping. A comparison between the measured and computed downwash angles is shown in Figs. 5A to 5D. The illustrated profiles are taken along the horizontal line passing through the center of the experimentally observed vortex (Fig. 5A). Computed results are in reasonable agreement with experiment.

Figures 6 to 11 illustrate the computed and measured normal force on a deflected fin attached to a tangent-ogive body. Both inviscid and clipped

results are shown with the fin located at different body roll positions. Variations in computed inviscid and clipped flow properties upstream of the fin are illustrated in Figs. 7 and 8A to 8H.

Leeside fin force data computed with clipping at Mach 2 (Figs. 9A to 9E) are in better agreement with experiment than when computed without it. On the windward side little difference is noted. Similar observations can be made for the Mach 3 flow (Figs.10A to 10F). At Mach 4.5 results are given in Figs. 11A to 11D.

CONCLUDING REMARKS

A simple method has been developed to model crossflow separation for inviscid (Euler type) computations by clipping the crossflow velocity near the body surface. The method has been validated for a tangent-ogive-cylinder body of circular cross-section and shown to be useful at supersonic speeds at low to intermediate angles of incidence ($M < 5$, $\alpha < 20$ deg). At low Mach numbers ($M < 3$), the method offers a significant improvement in the inviscid leeside surface pressure distributions and also yields improved prediction of aerodynamic coefficient. At higher Mach numbers, especially at higher angles of attack, the leeside pressure becomes very low making such modeling of little interest in body or fin force computations. Clipping also improves the robustness of a space-marching type computation by suppressing the crossflow shock. Further investigation of this method, especially its application to bodies of non-circular cross-section is considered warranted.

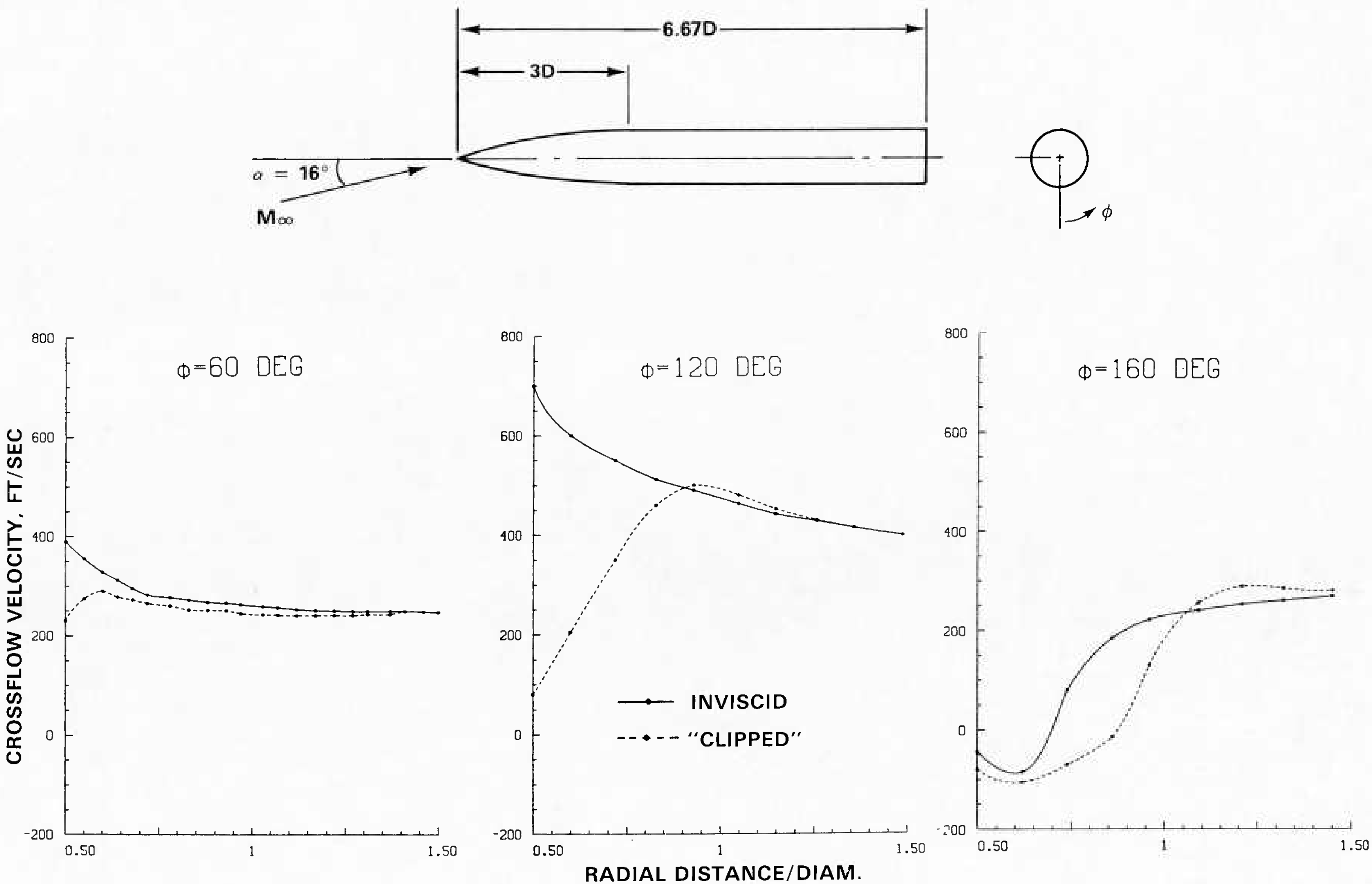


FIGURE 1. CROSSFLOW VELOCITY PROFILES FOR AN OGIVE-CYLINDER AT $M_\infty = 2.96$, $\alpha = 16$ DEG

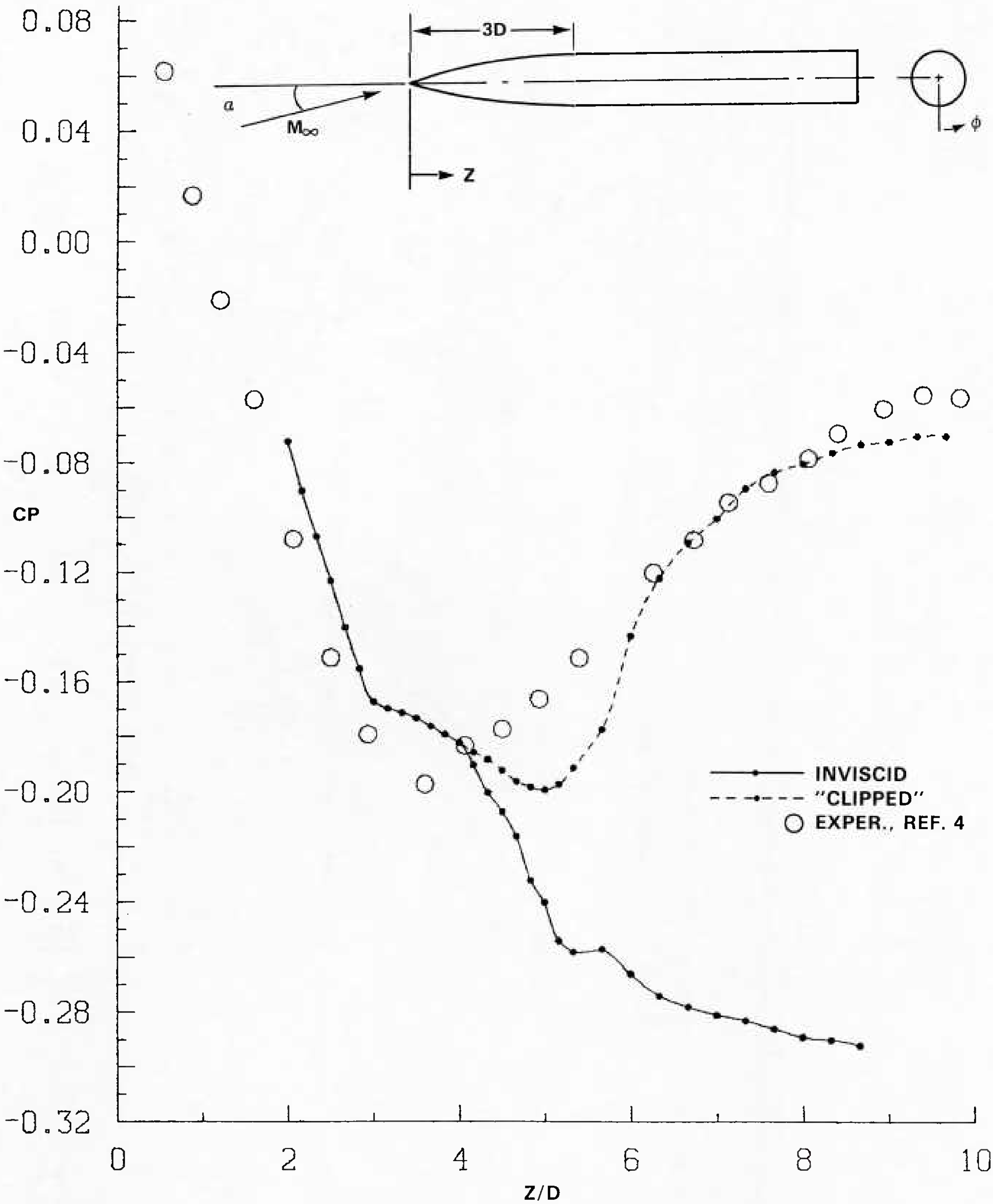


FIGURE 2. COMPARISON OF SURFACE PRESSURE PROFILES FOR AN OGIVE-CYLINDER BODY
A. LONGITUDINAL PLANE AT ϕ = 105 DEG, M_∞ = 1.98, α = 15 DEG

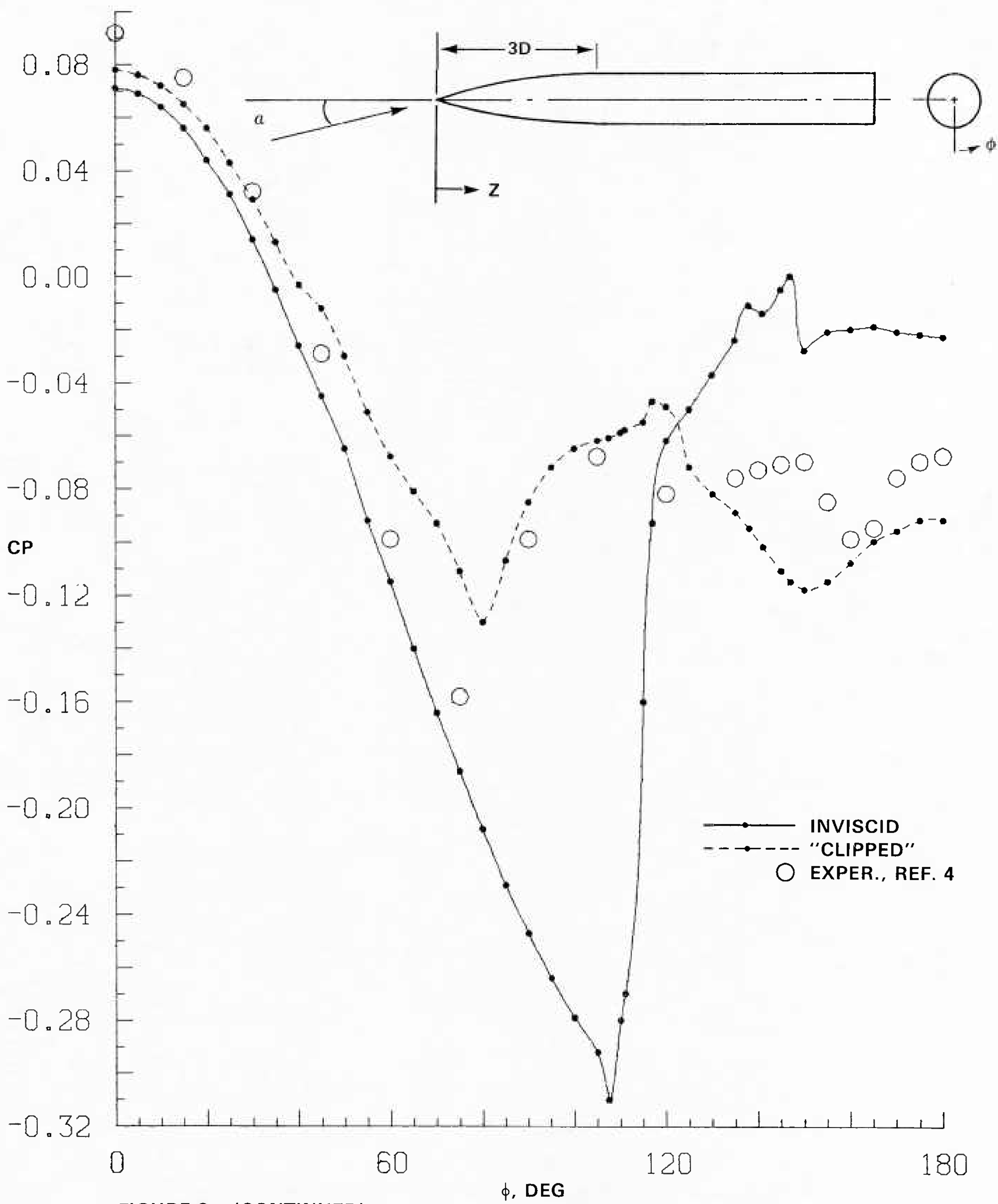
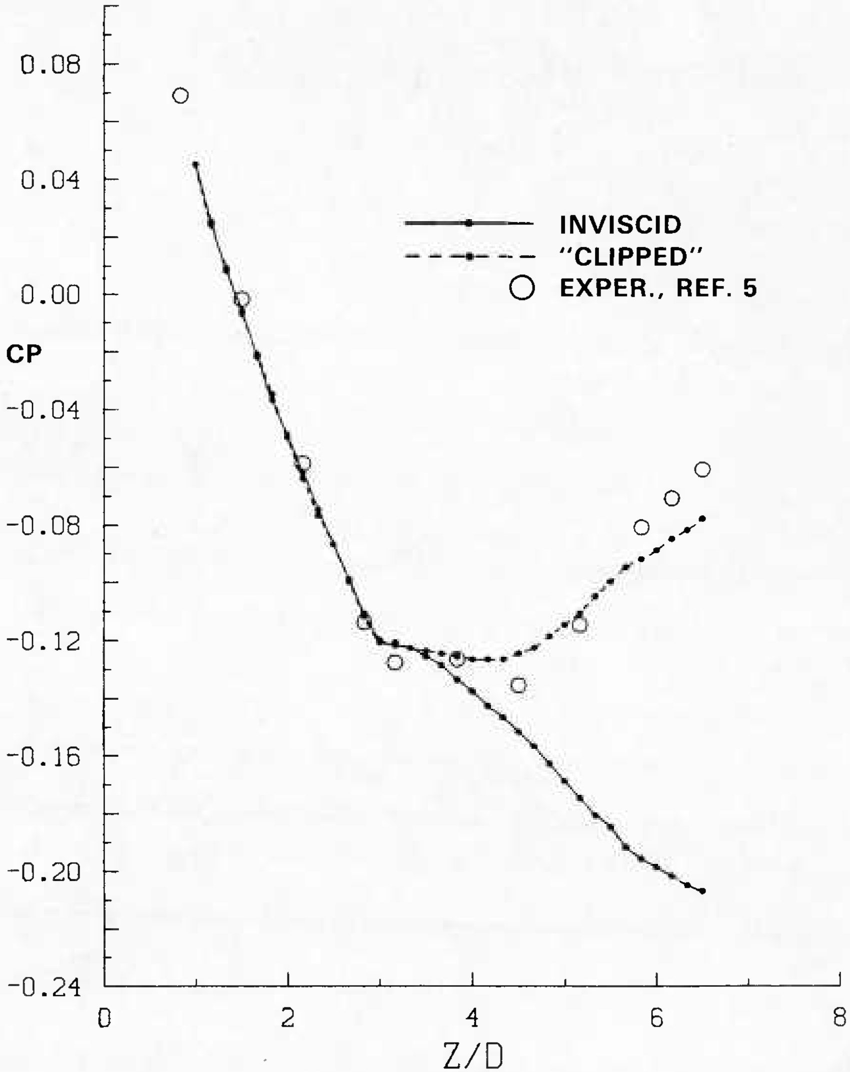
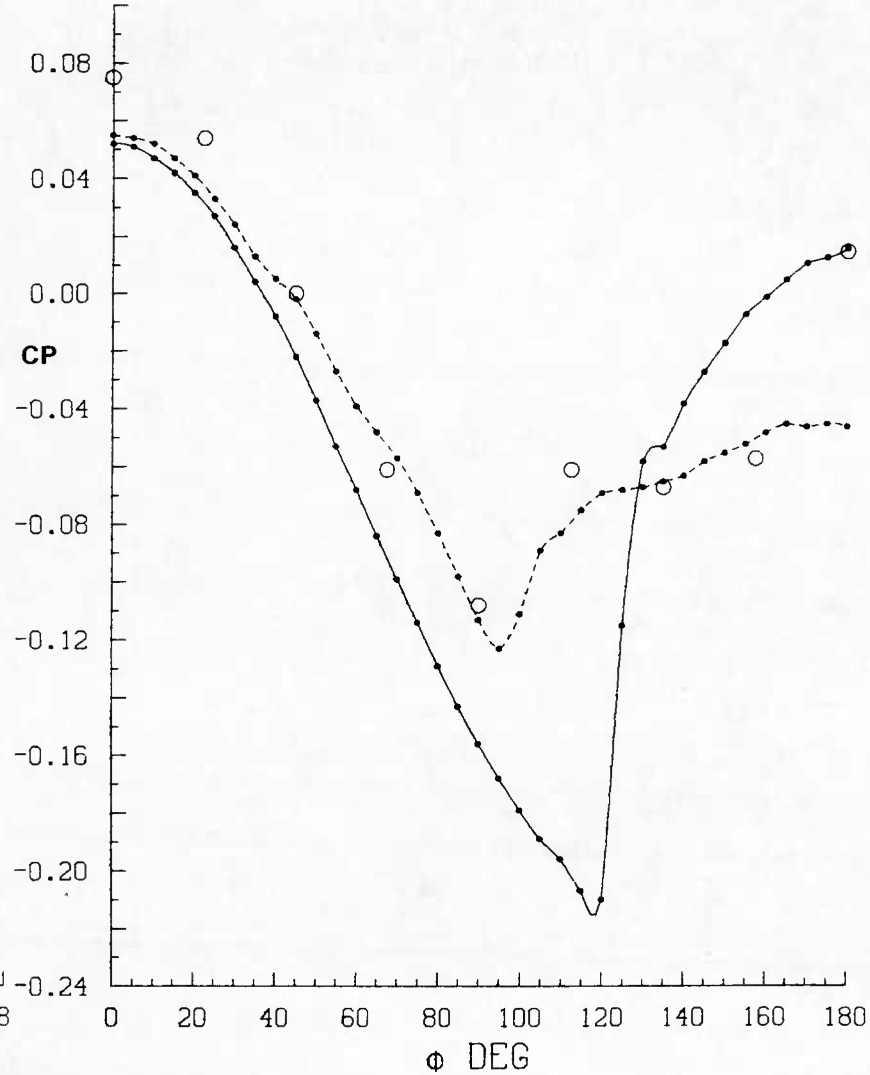


FIGURE 2. (CONTINUED)

B. CROSSFLOW PLANE AT Z = 8.5D, M_∞ = 1.98, α = 15 DEG

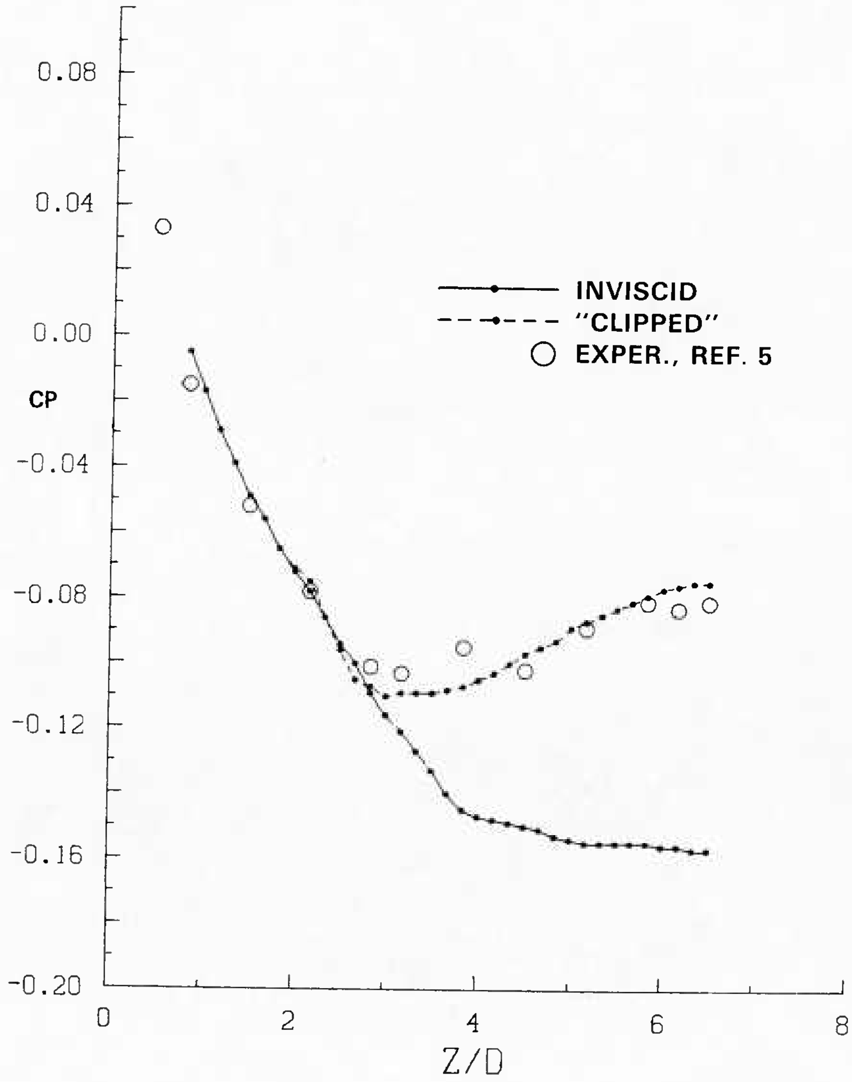


C. LONGITUDINAL PLANE AT ϕ = 115 DEG
M_∞ = 2.3, α = 12 DEG

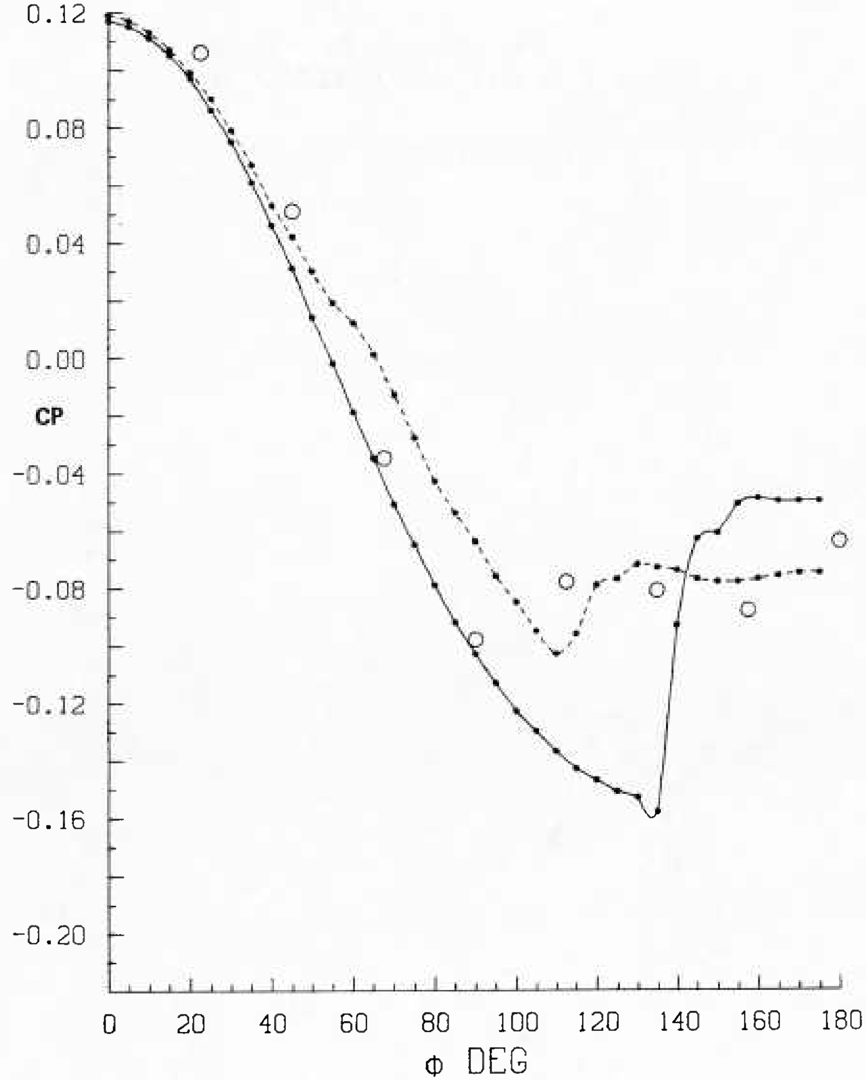


D. CROSSFLOW PLANE AT Z = 6.5D
M_∞ = 2.3, α = 12 DEG

FIGURE 2. (CONTINUED)

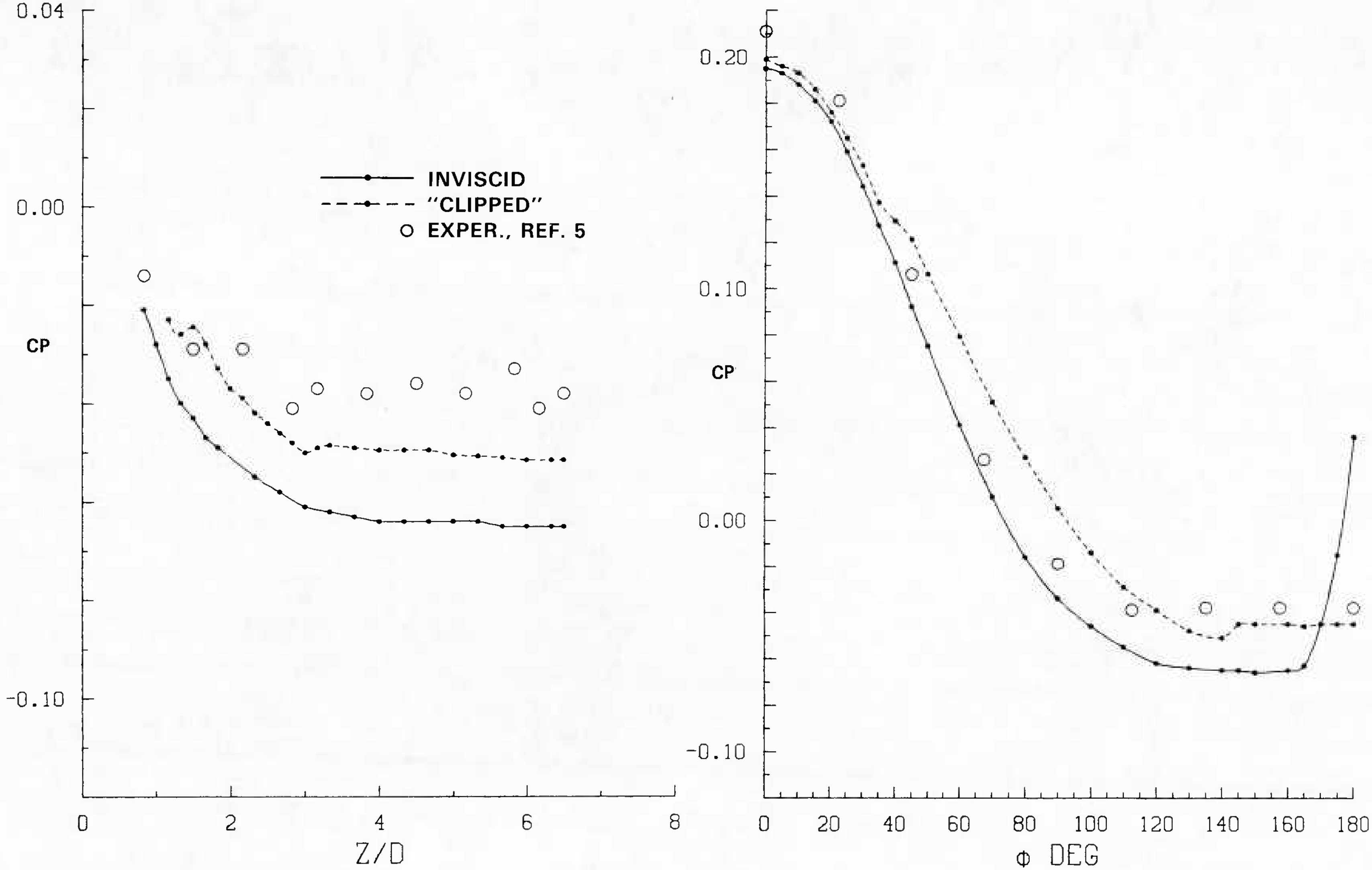


E. LONGITUDINAL PLANE AT ϕ = 135 DEG
M_∞ = 2.96, α = 16 DEG



F. CROSSFLOW PLANE AT Z = 6.5D
M_∞ = 2.96, α = 16 DEG

FIGURE 2. (CONTINUED)



G. LONGITUDINAL PLANE AT ϕ = 135 DEG
M_∞ = 4.63, α = 20 DEG

H. CROSSFLOW PLANE AT Z = 6.5D
M_∞ = 4.63, α = 20 DEG

FIGURE 2. (CONCLUDED)

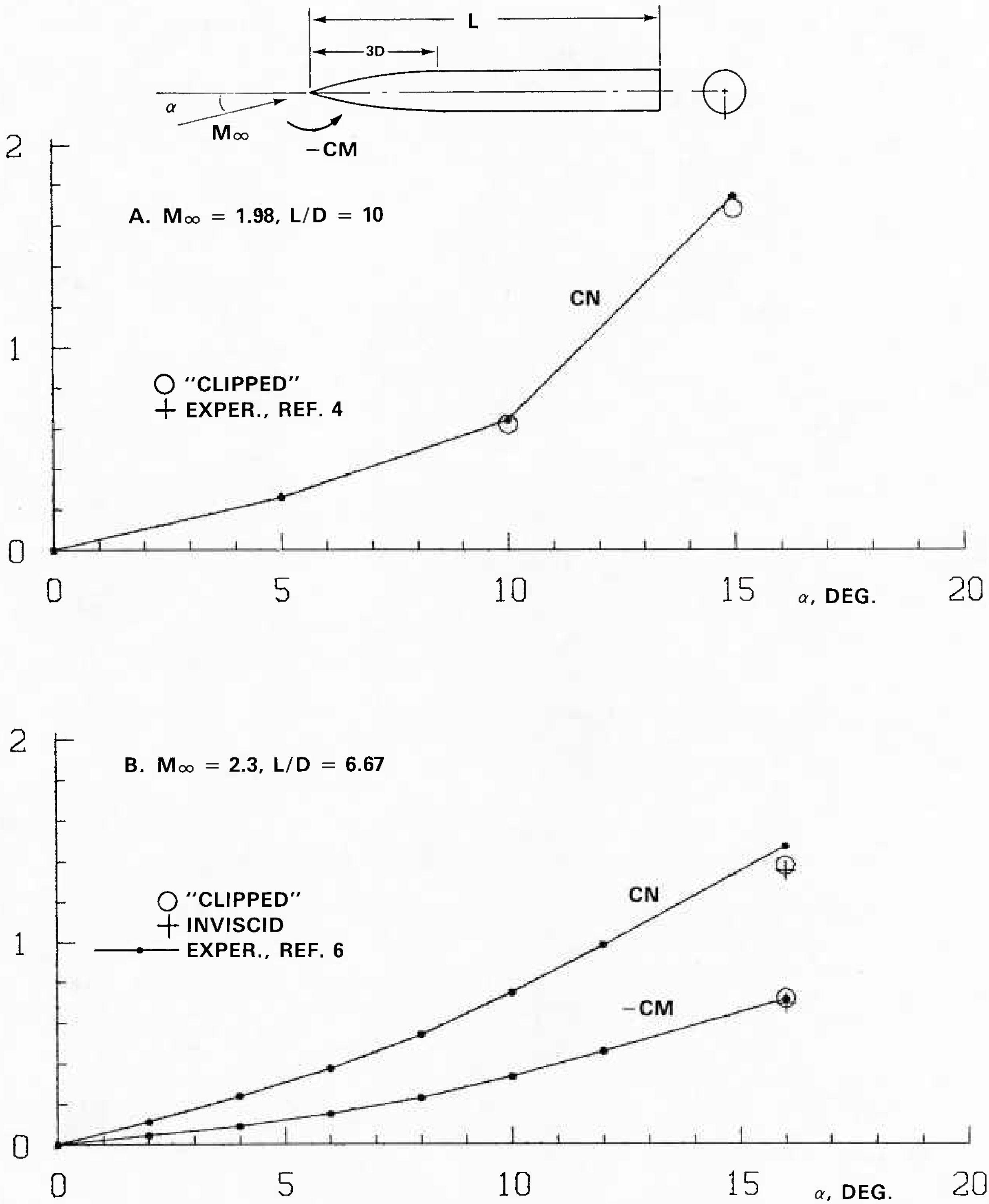
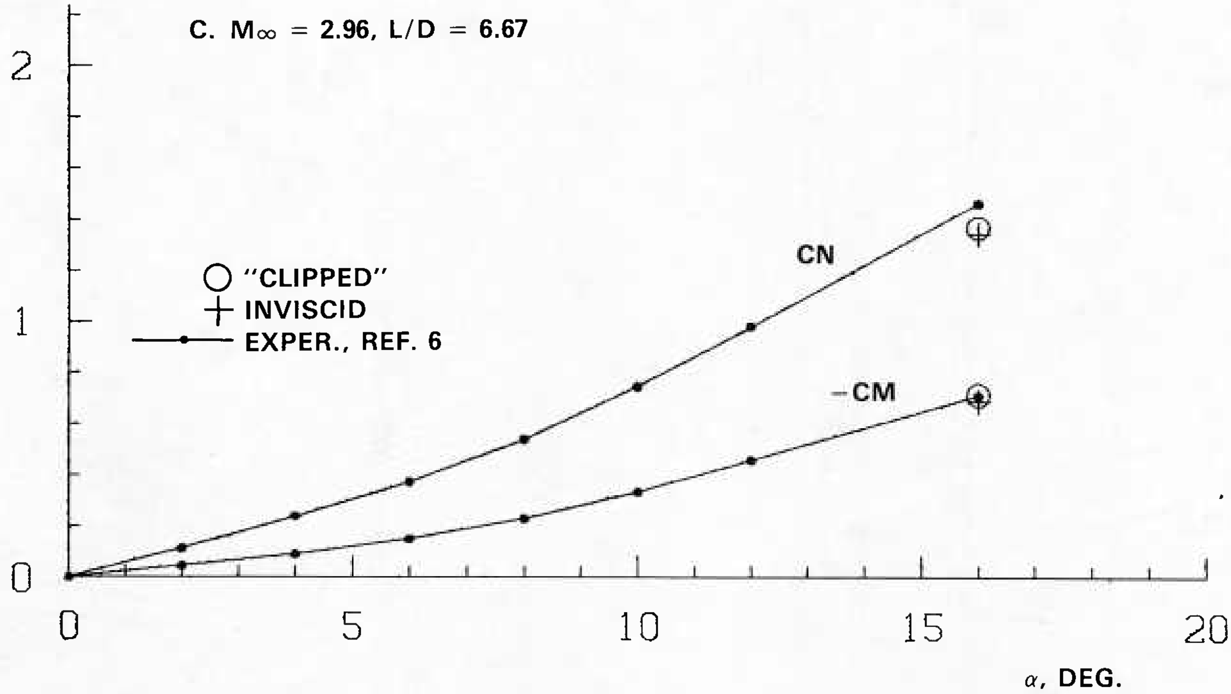
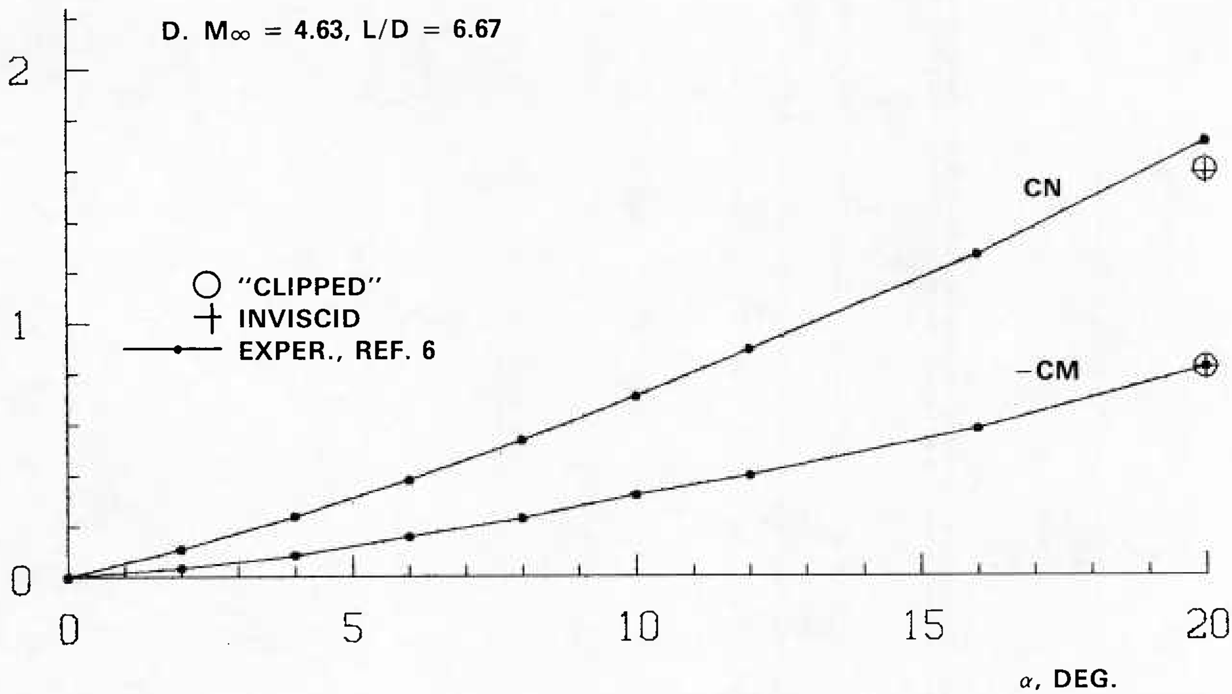


FIGURE 3. COMPARISON OF NORMAL FORCE AND PITCHING MOMENT COEFFICIENTS FOR A TANGENT-OGIVE-CYLINDER BODY





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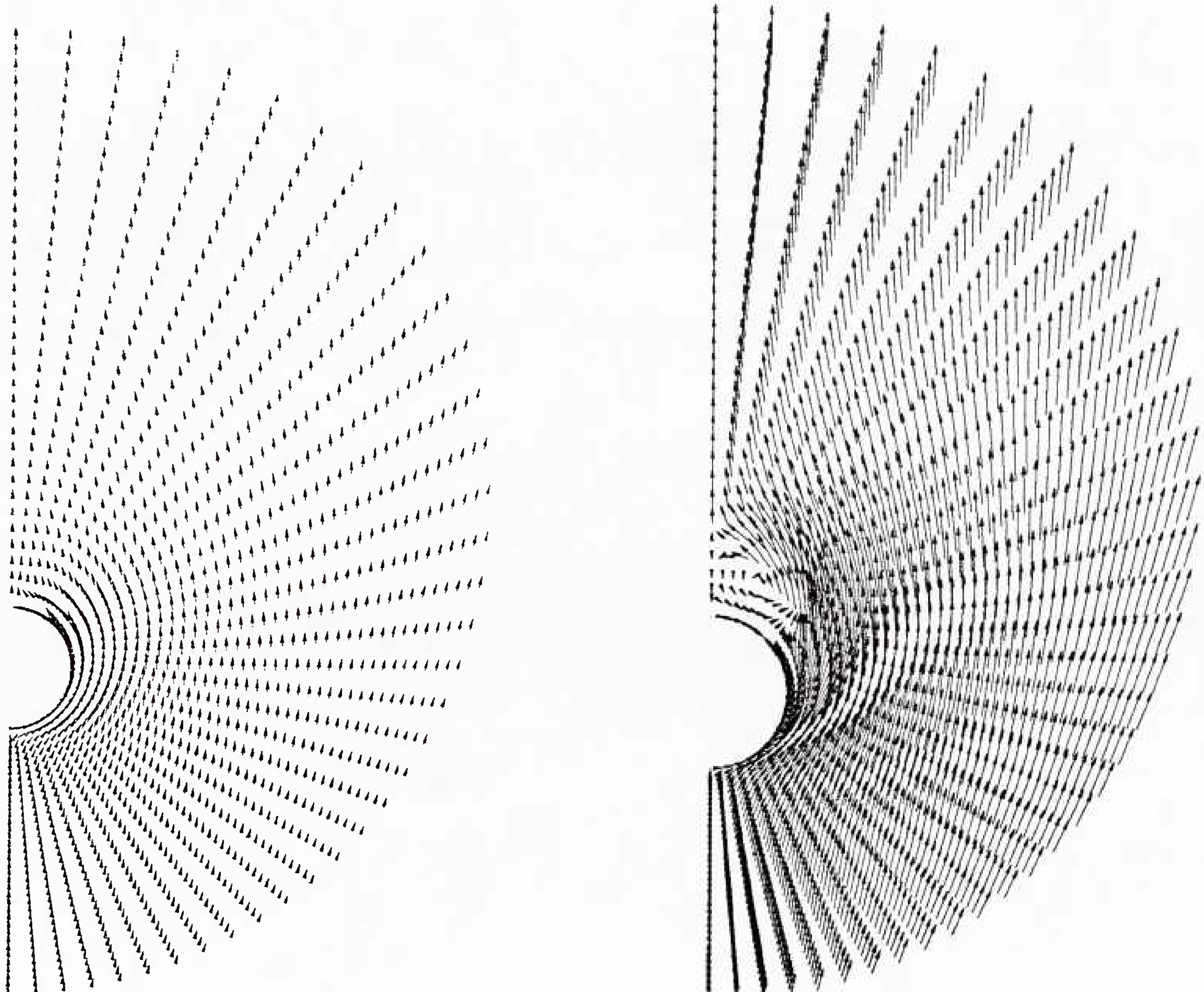
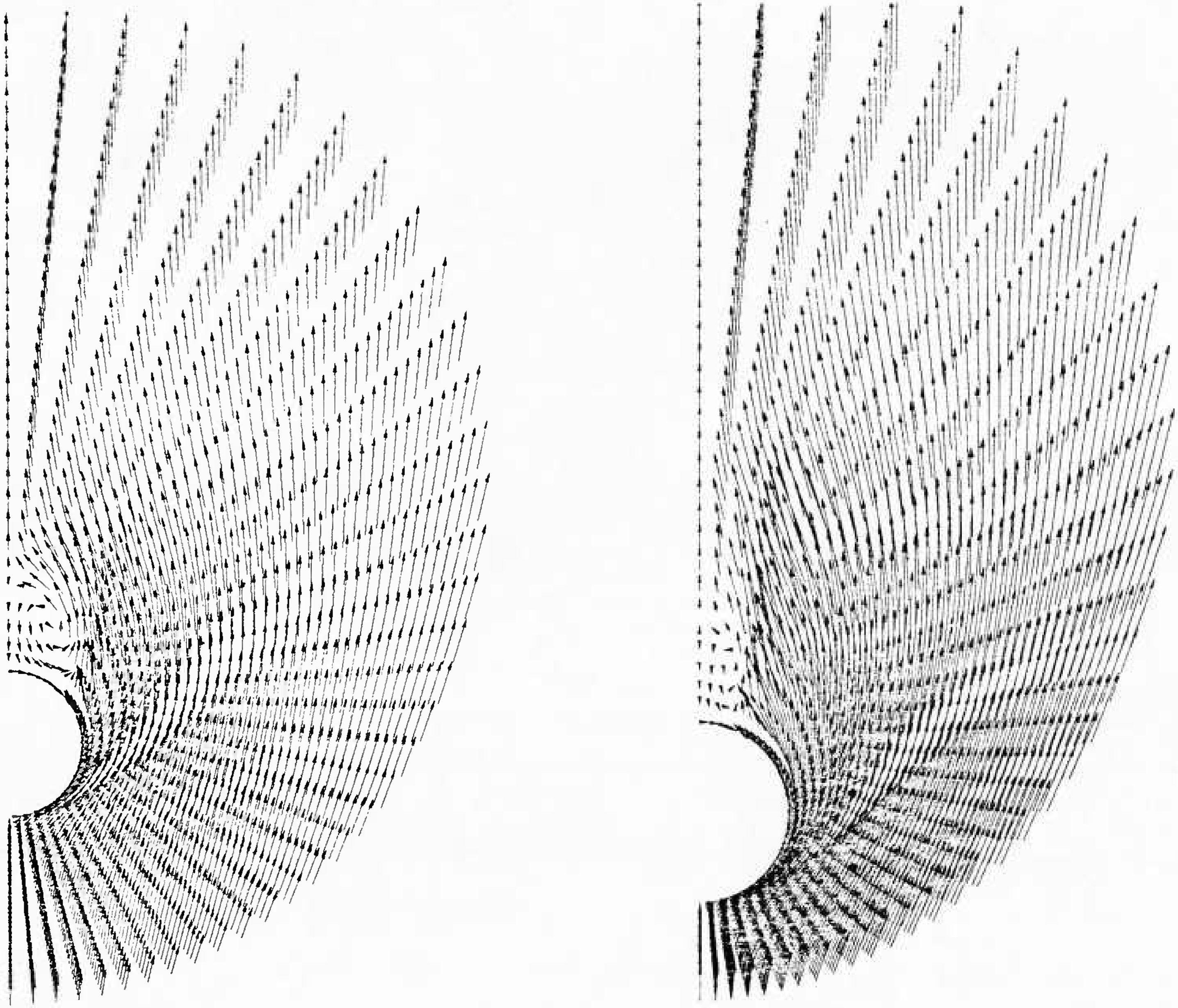


A. INVISCID
$M_\infty = 2.3$, $\alpha = 12$ DEG., $Z = 6.67D$

B. "CLIPPED"
$M_\infty = 2.3$, $\alpha = 12$ DEG., $Z = 6.67D$

FIGURE 4. COMPUTED CROSSFLOW VELOCITY VECTORS



C. "CLIPPED"
M_∞ = 2.96, α = 16 DEG., Z = 6.67D

D. "CLIPPED"
M_∞ = 4.63, α = 20 DEG., Z = 6.67D

FIGURE 4. (CONTINUED)

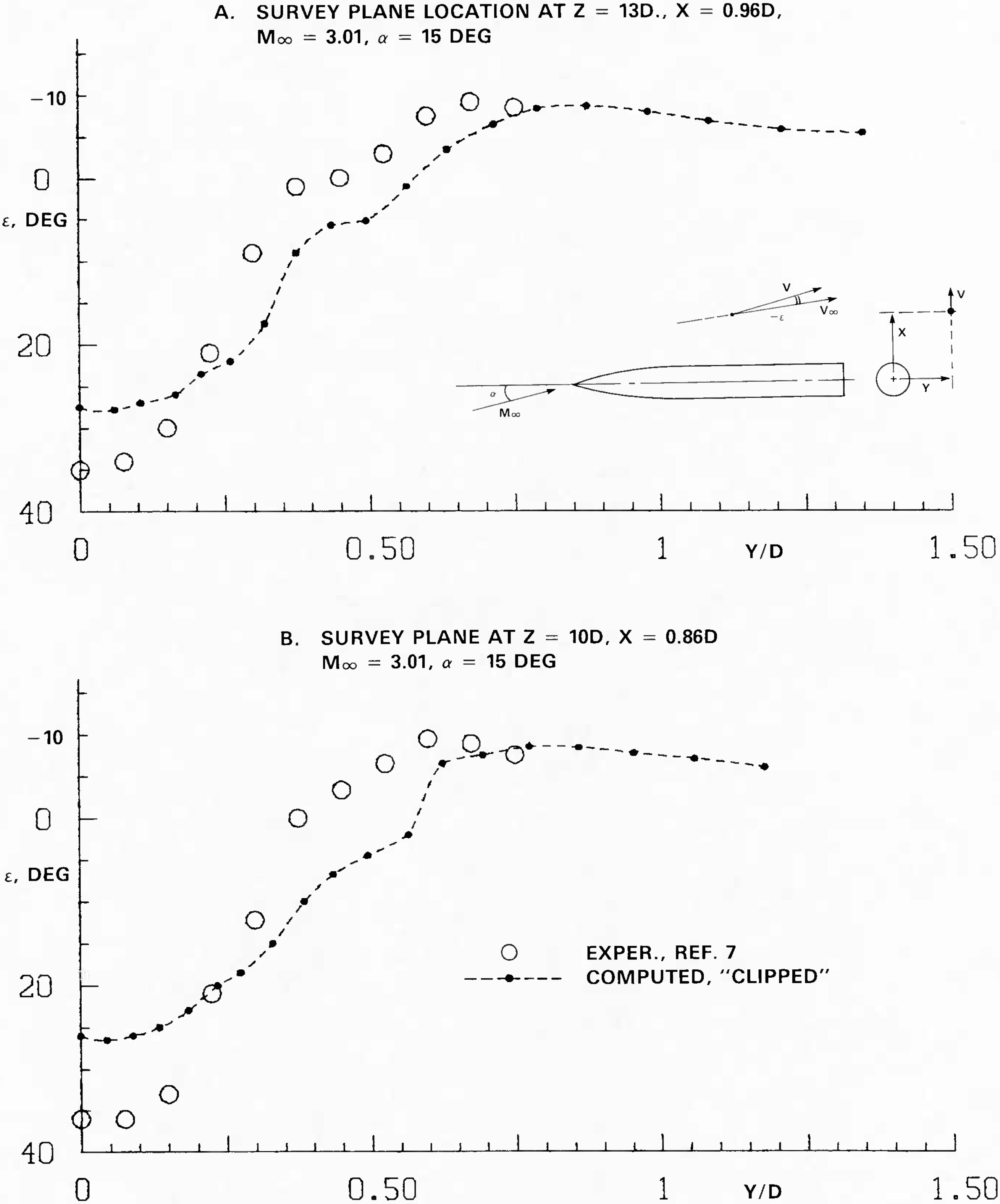
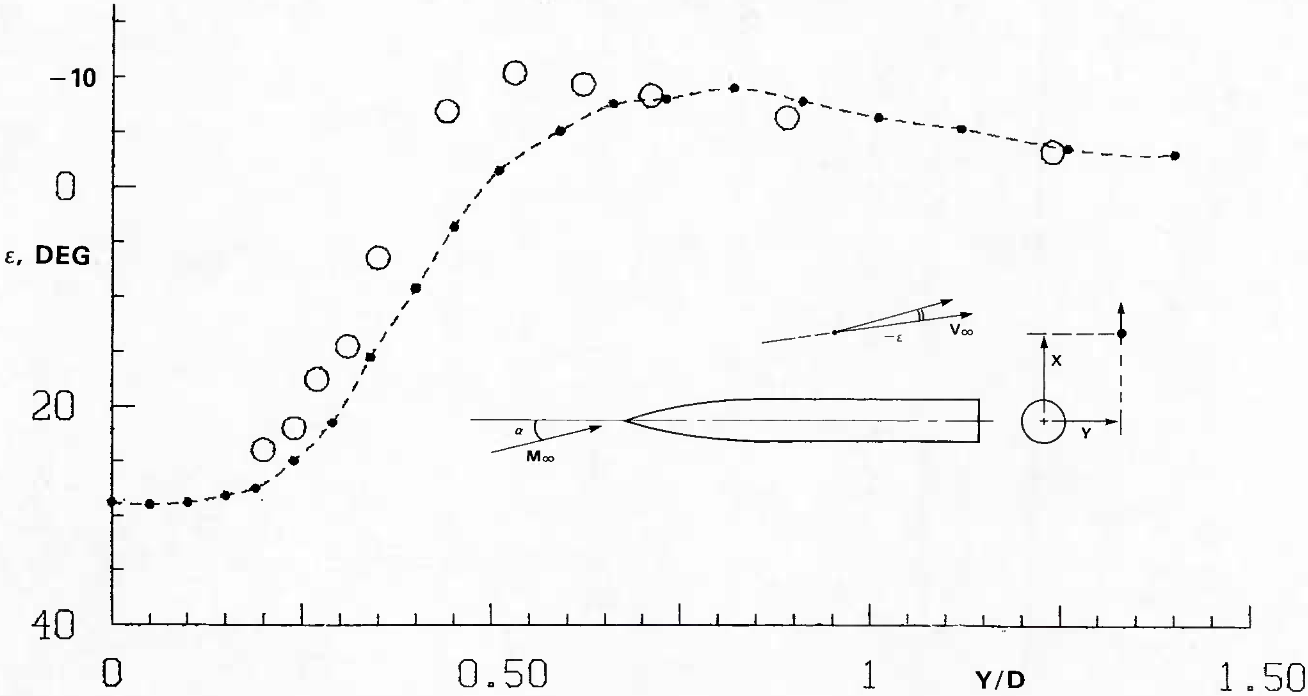
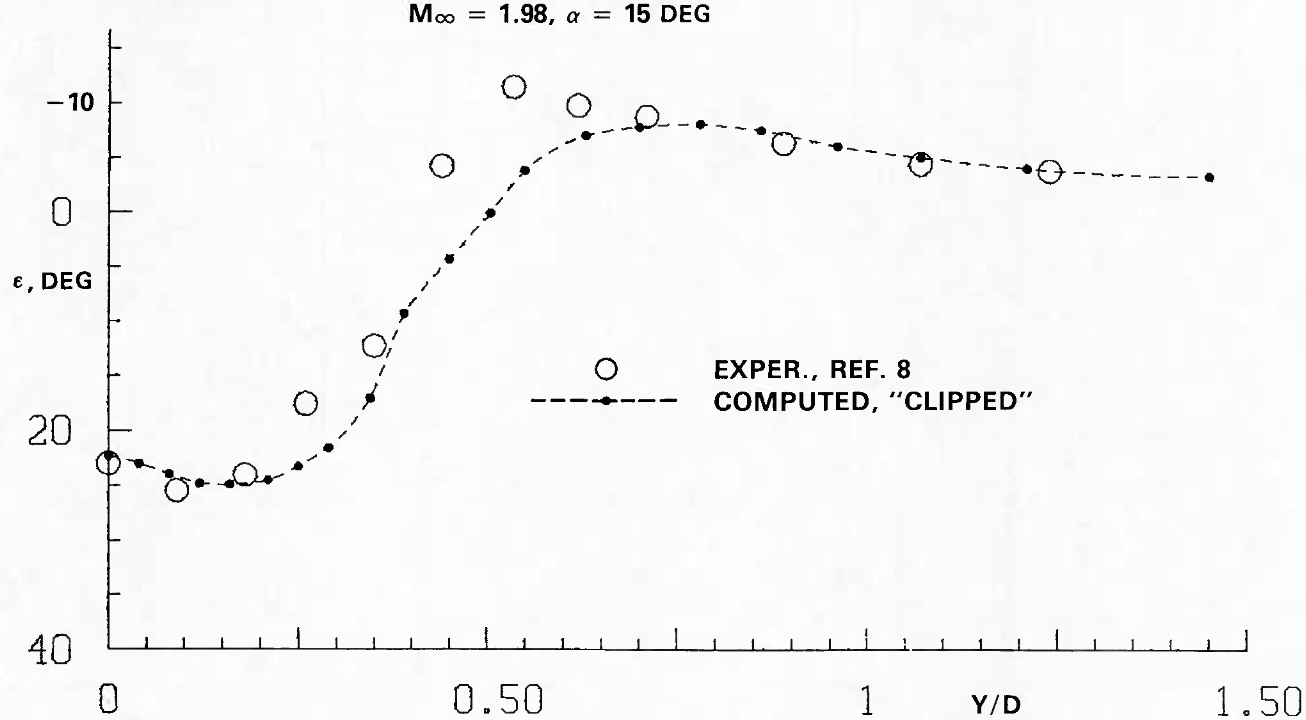


FIGURE 5. COMPARISON OF LEESIDE DOWNWASH ANGLE

C. SURVEY PLANE AT Z = 10D, X = 0.91D
M_∞ = 1.98, α = 15 DEG



D. SURVEY PLANE AT Z = 8.8D., X = 0.78D,
M_∞ = 1.98, α = 15 DEG



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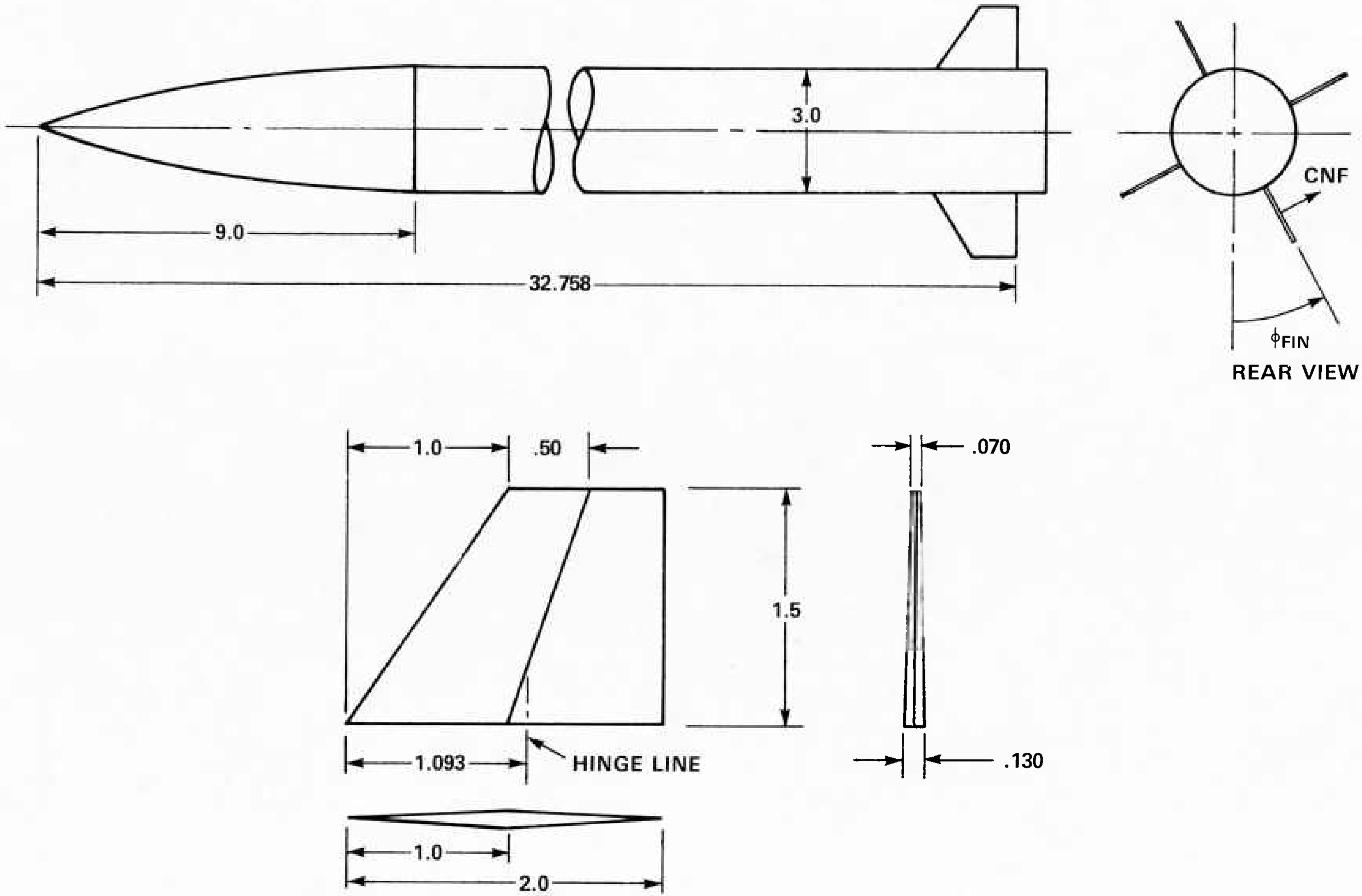


FIGURE 6. MODEL GEOMETRY FOR FIN FORCE COMPARISONS (REF. 9)

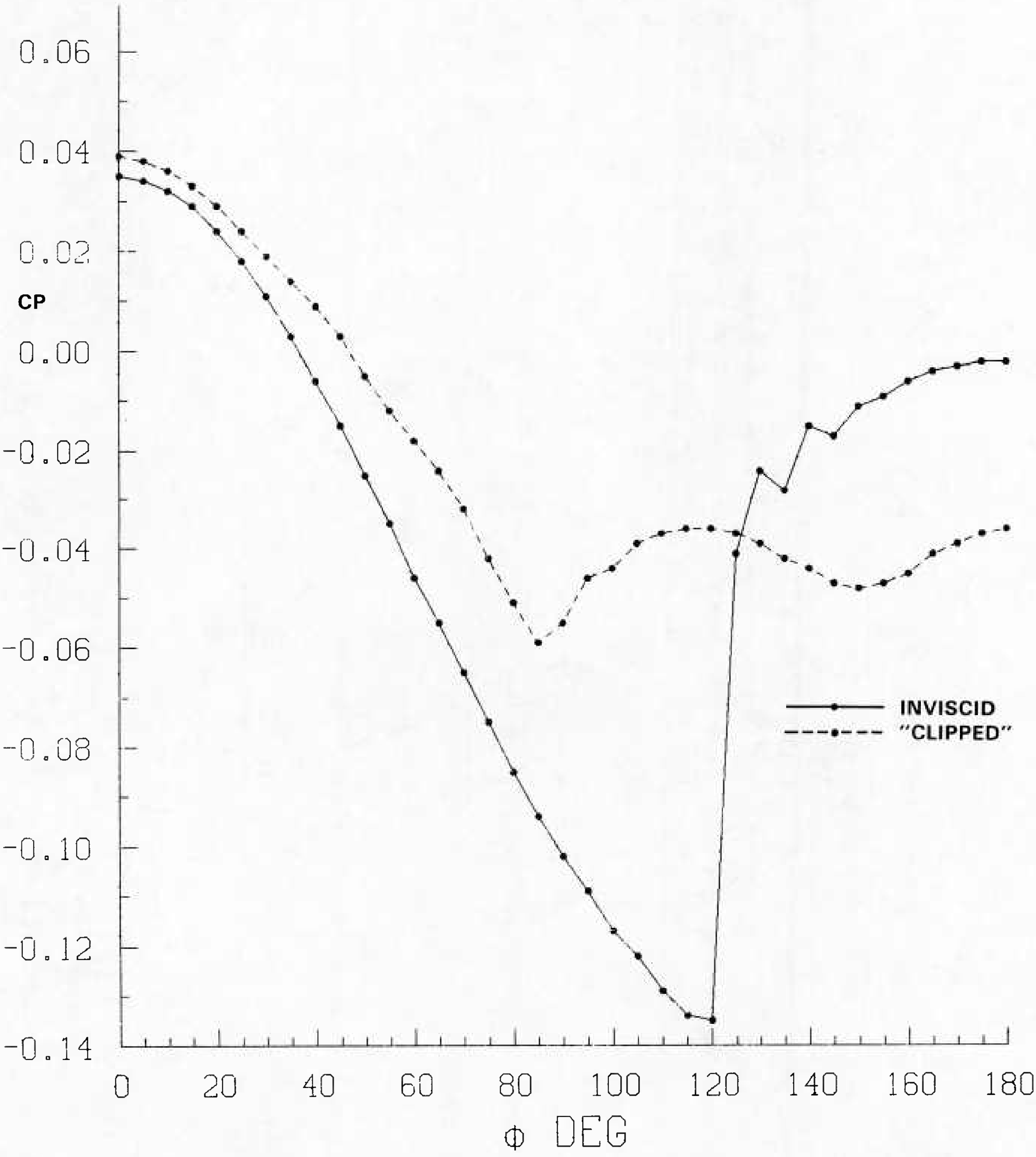


FIGURE 7. CIRCUMFERENCIAL SURFACE PRESSURE VARIATION AHEAD OF THE FINS (Z = 10D) FOR A TANGENT-OGIVE-CYLINDER AT M_∞ = 3.0, α = 10 DEG.

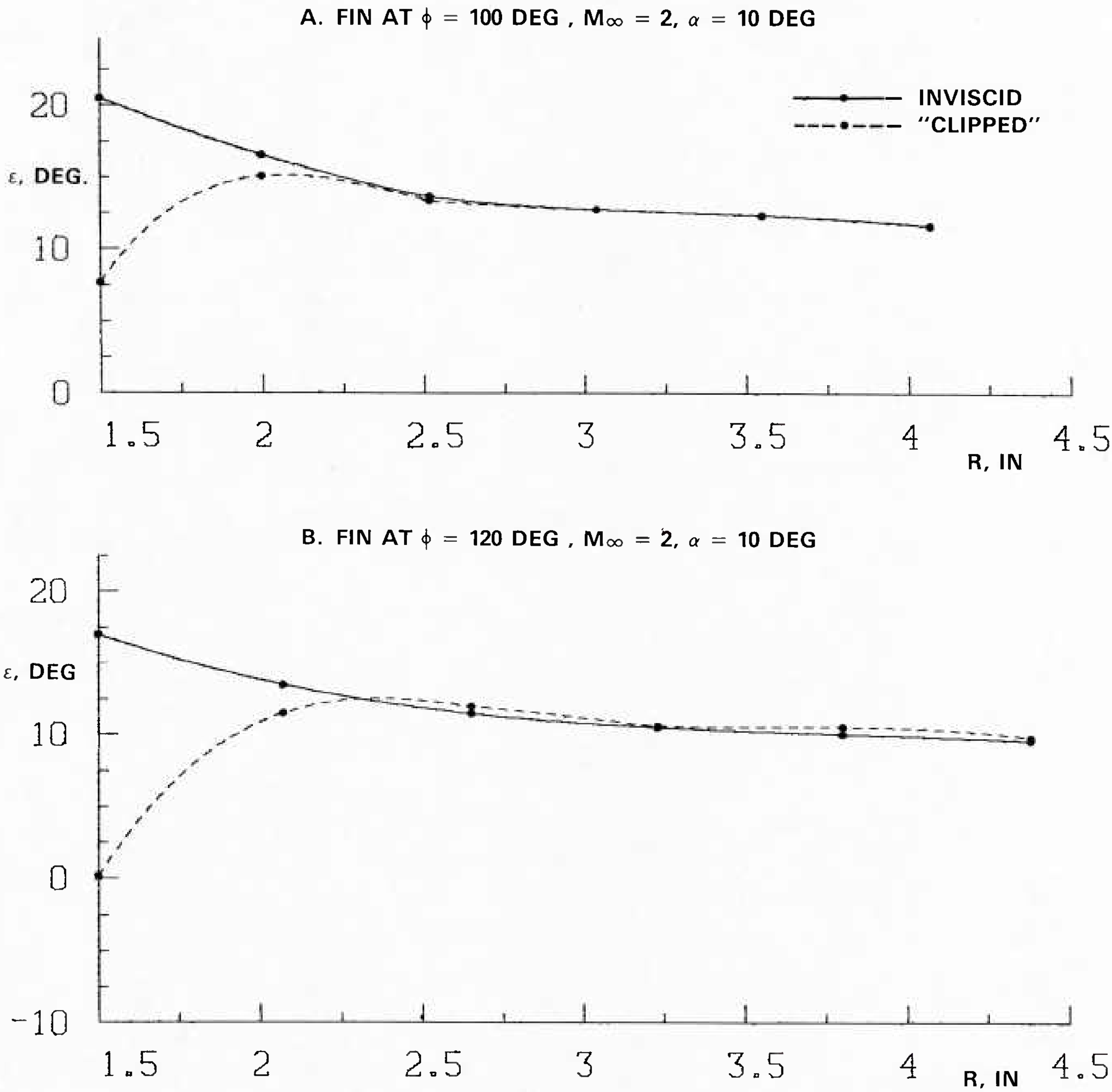
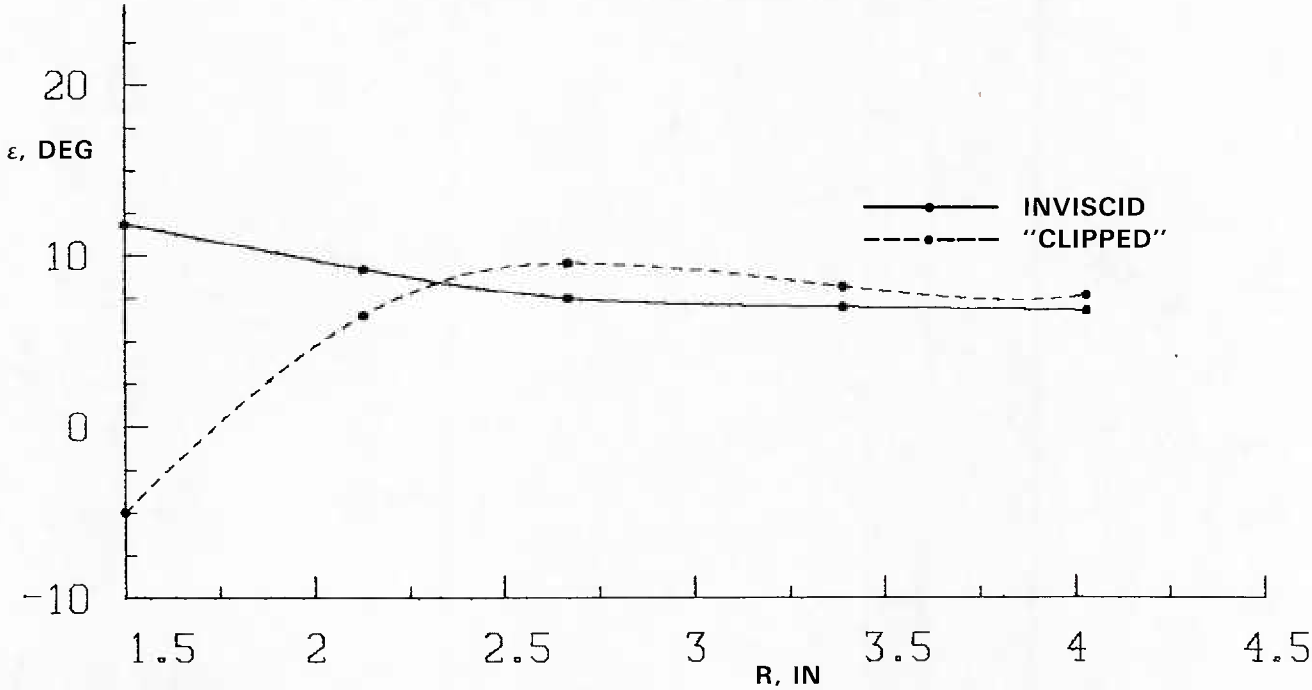


FIGURE 8. FLOW ANGLE RELATIVE TO FIN PLANE OF SYMMETRY, AS COMPUTED WITH AND WITHOUT CROSSFLOW MODIFICATION

C. FIN AT ϕ = 140 DEG , M_∞ = 2, α = 10 DEG



D. FIN AT ϕ = 160 DEG , M_∞ = 2, α = 10 DEG

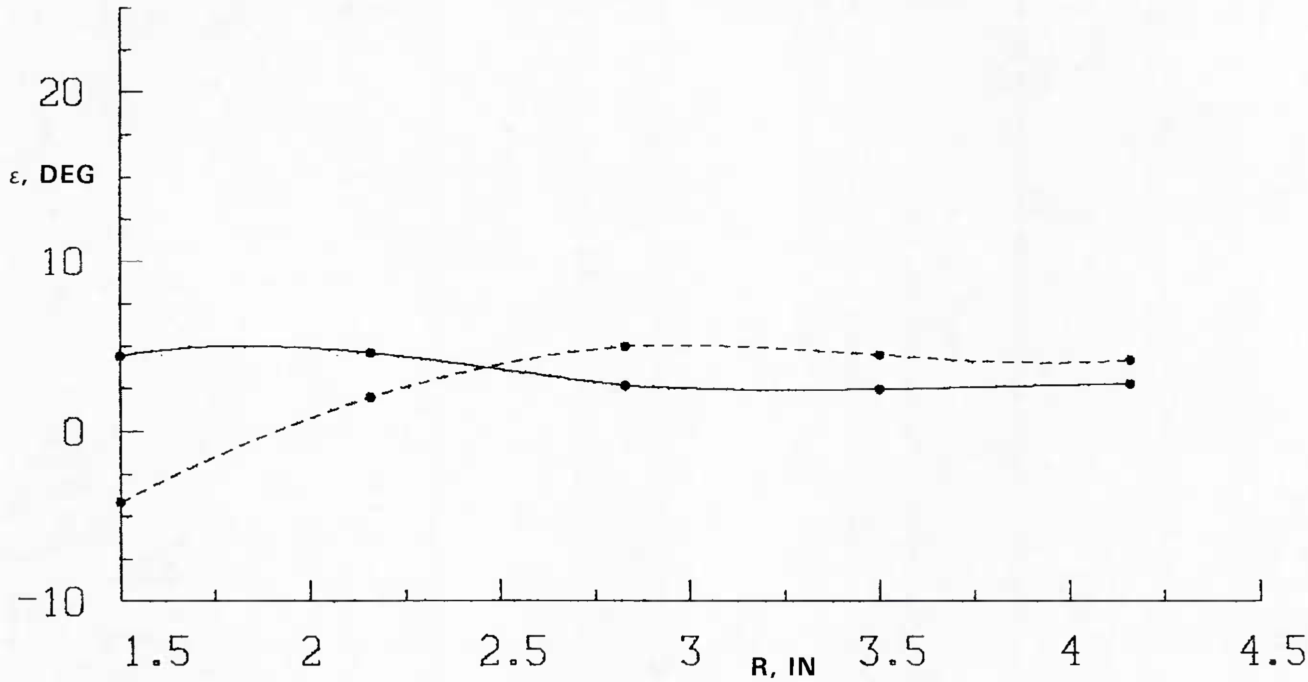
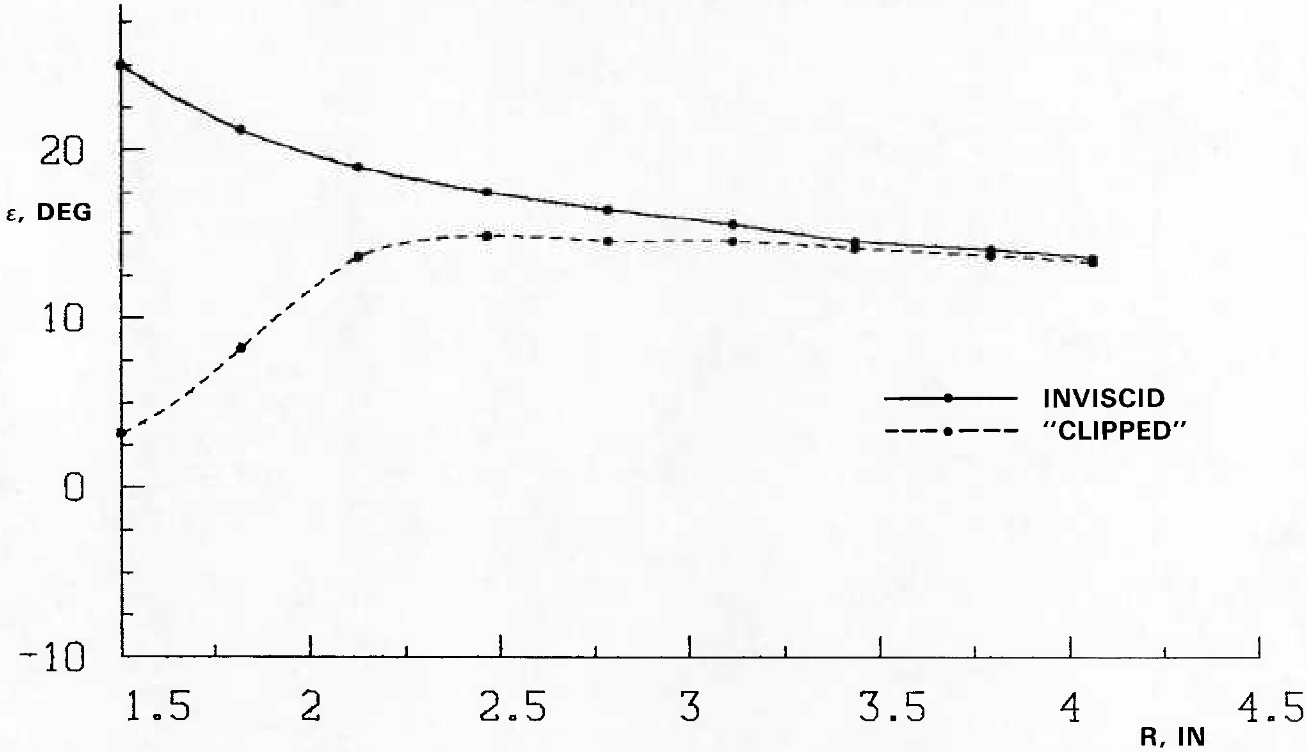


FIGURE 8. (CONTINUED)

E. FIN AT ϕ = 100 DEG , M_∞ = 3, α = 10 DEG



F. FIN AT ϕ = 120 DEG , M_∞ = 3, α = 10 DEG

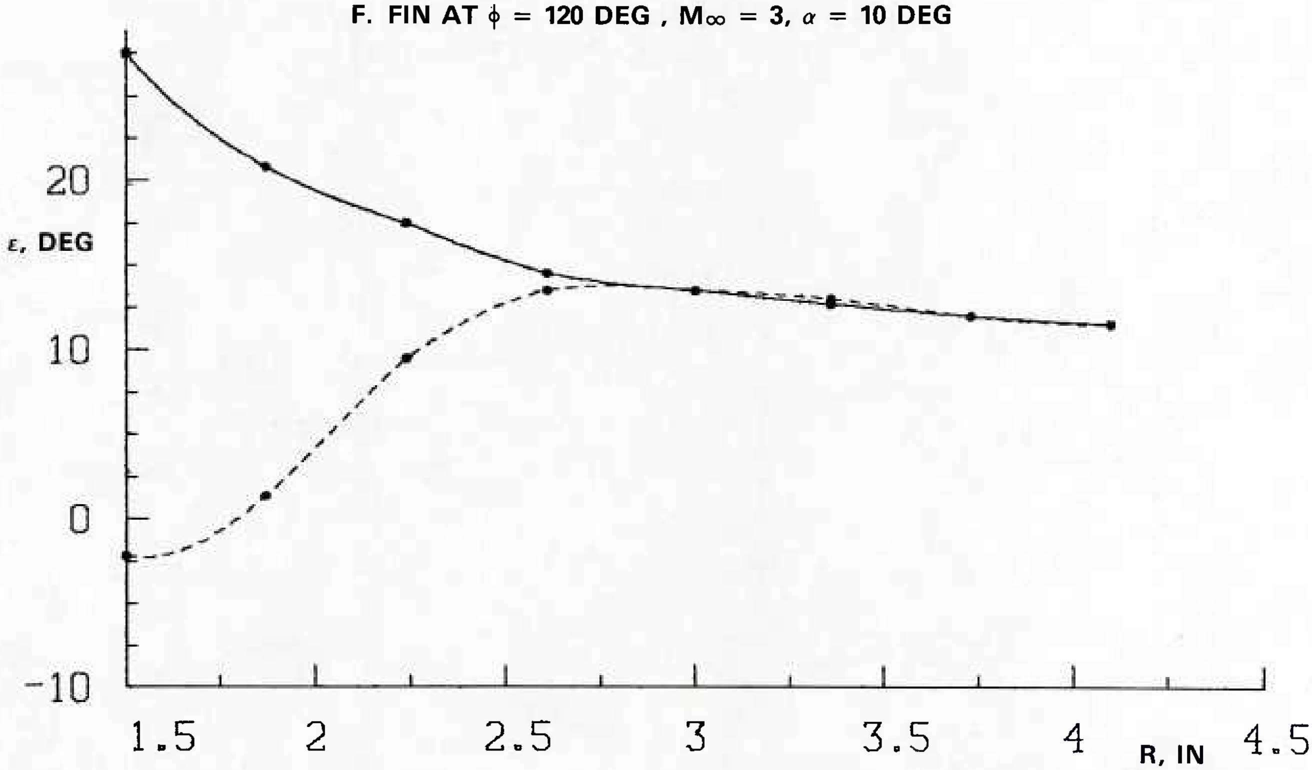
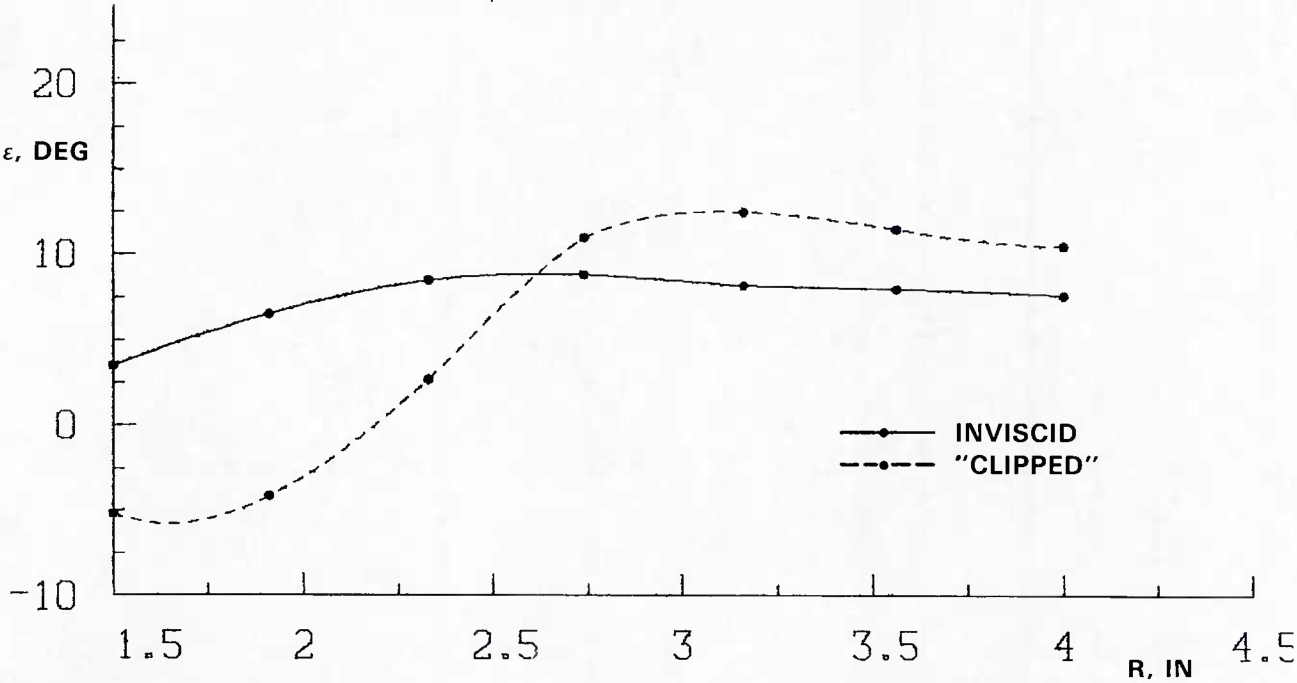
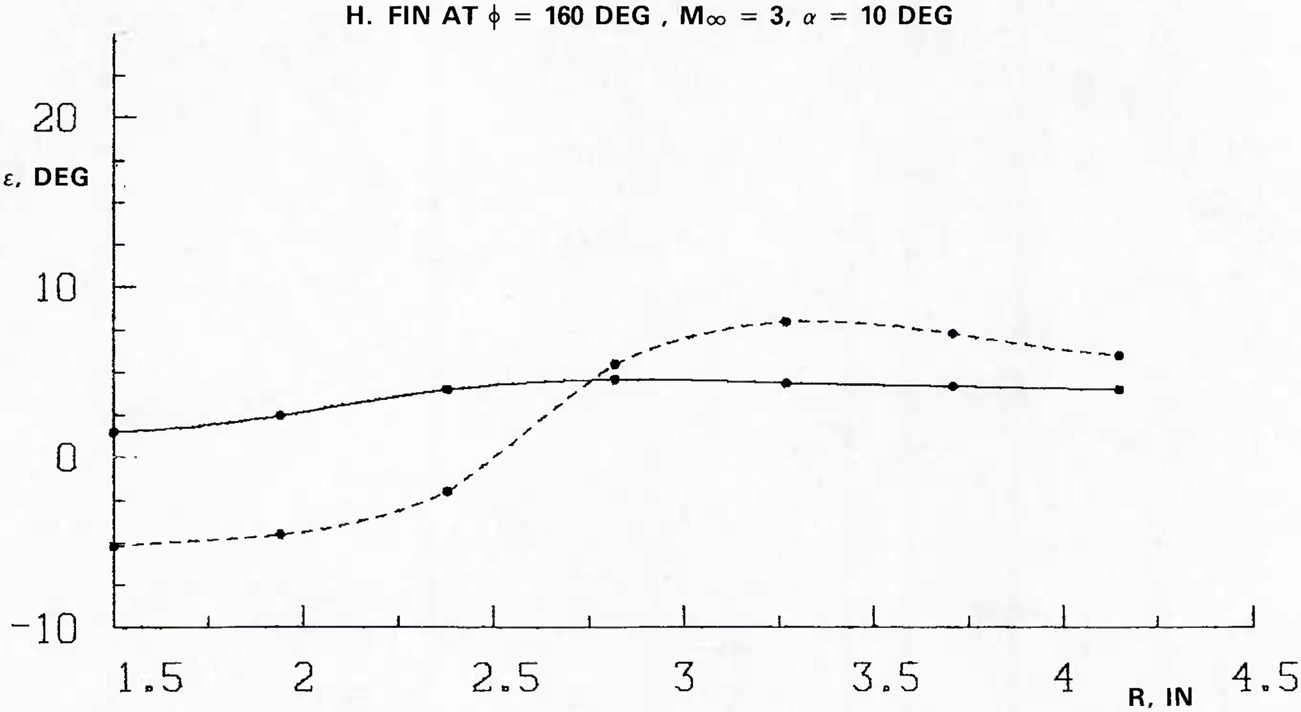


FIGURE 8. (CONTINUED)

G. FIN AT ϕ = 140 DEG , M_∞ = 3, α = 10 DEG



H. FIN AT ϕ = 160 DEG , M_∞ = 3, α = 10 DEG



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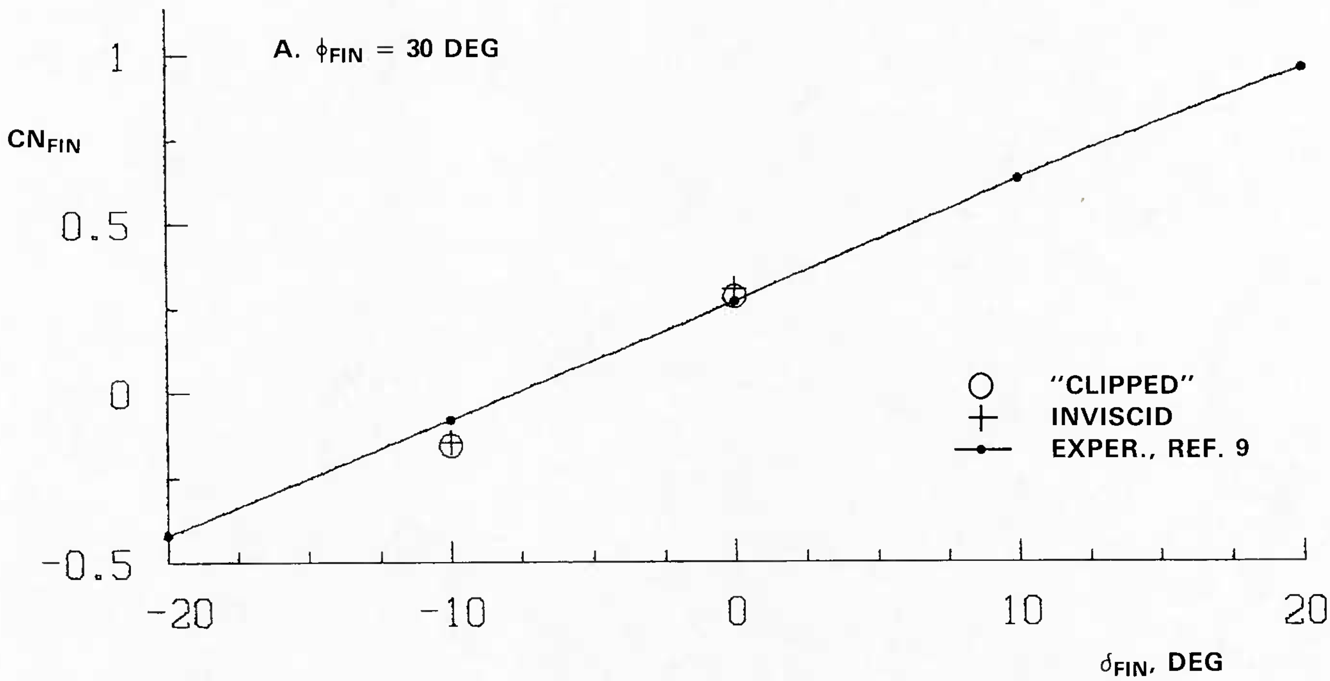


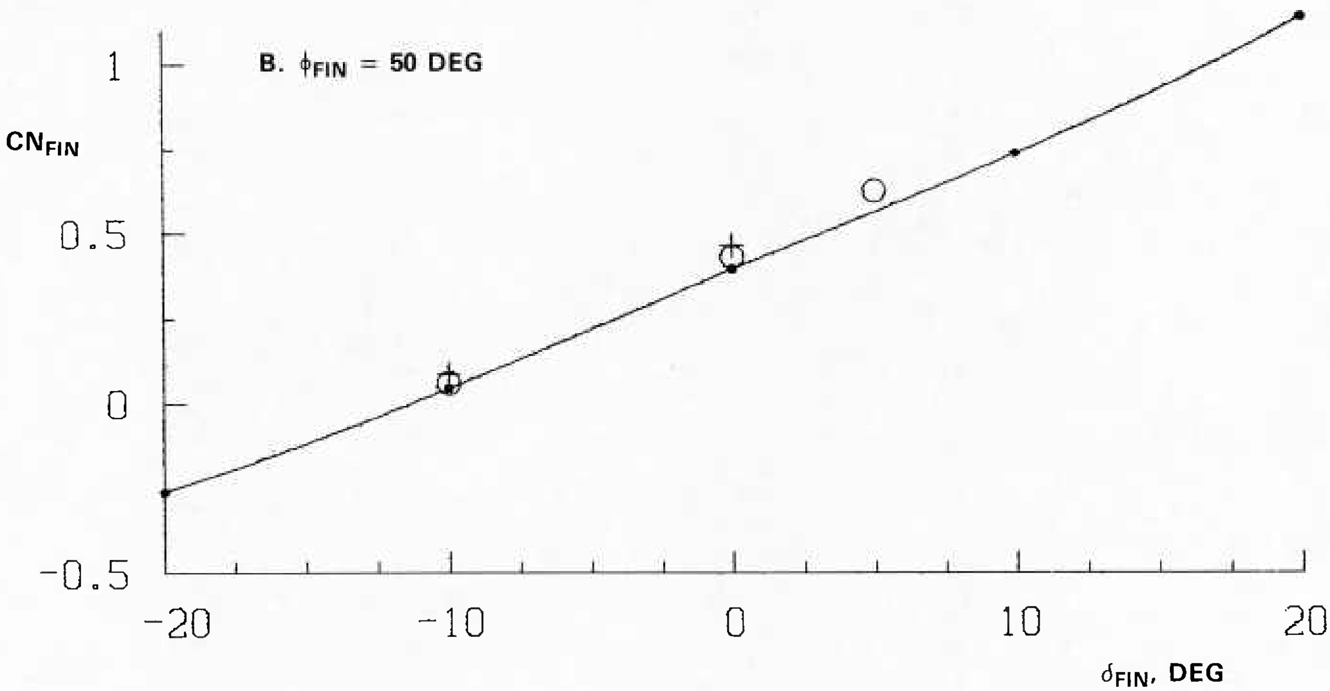
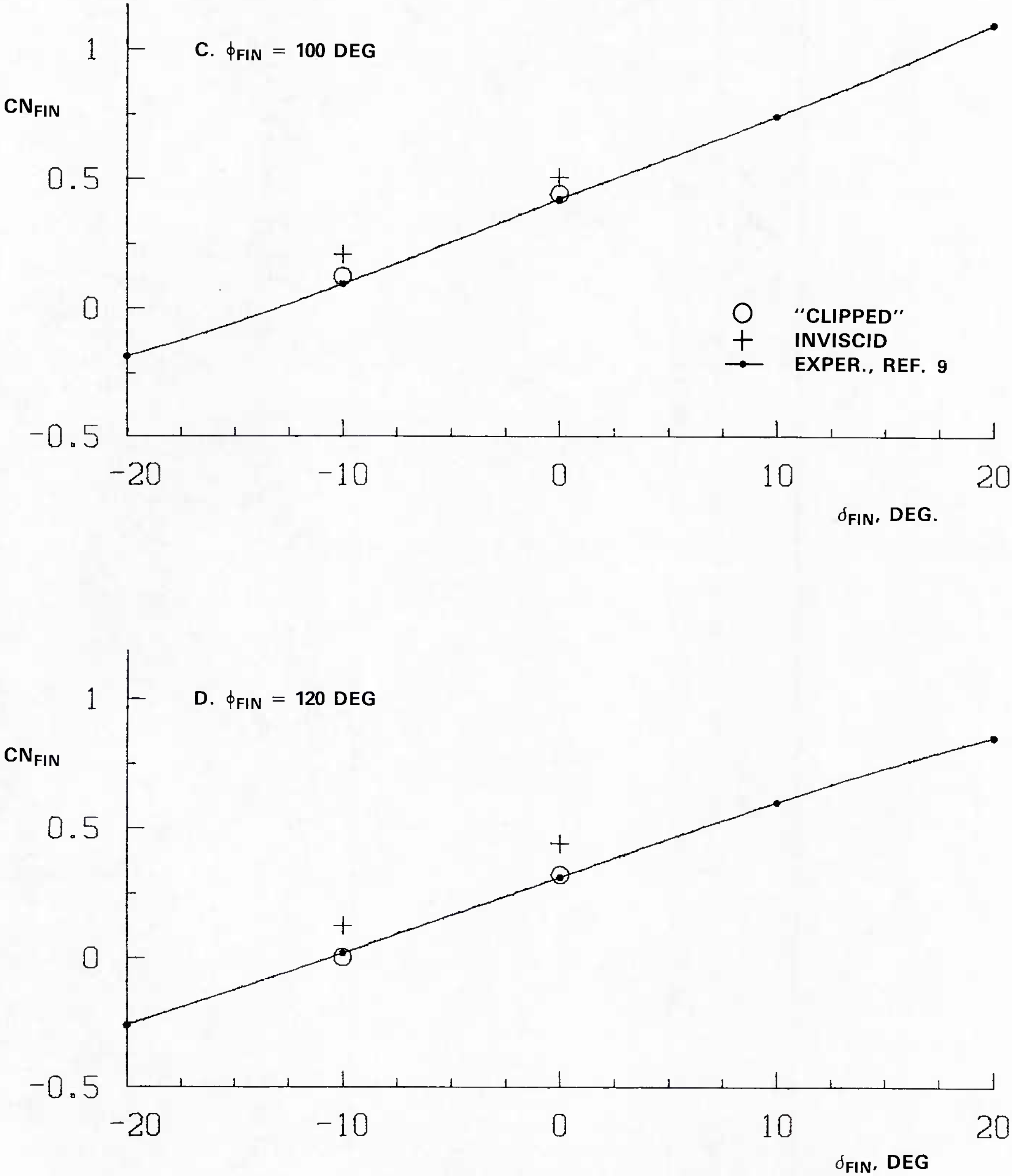


FIGURE 9. COMPARISON OF FIN NORMAL FORCE COEFFICIENT AT $M_\infty = 2$, $\alpha = 10$ DEG , (MODEL GEOMETRY AT SHOWN IN FIG. 6)



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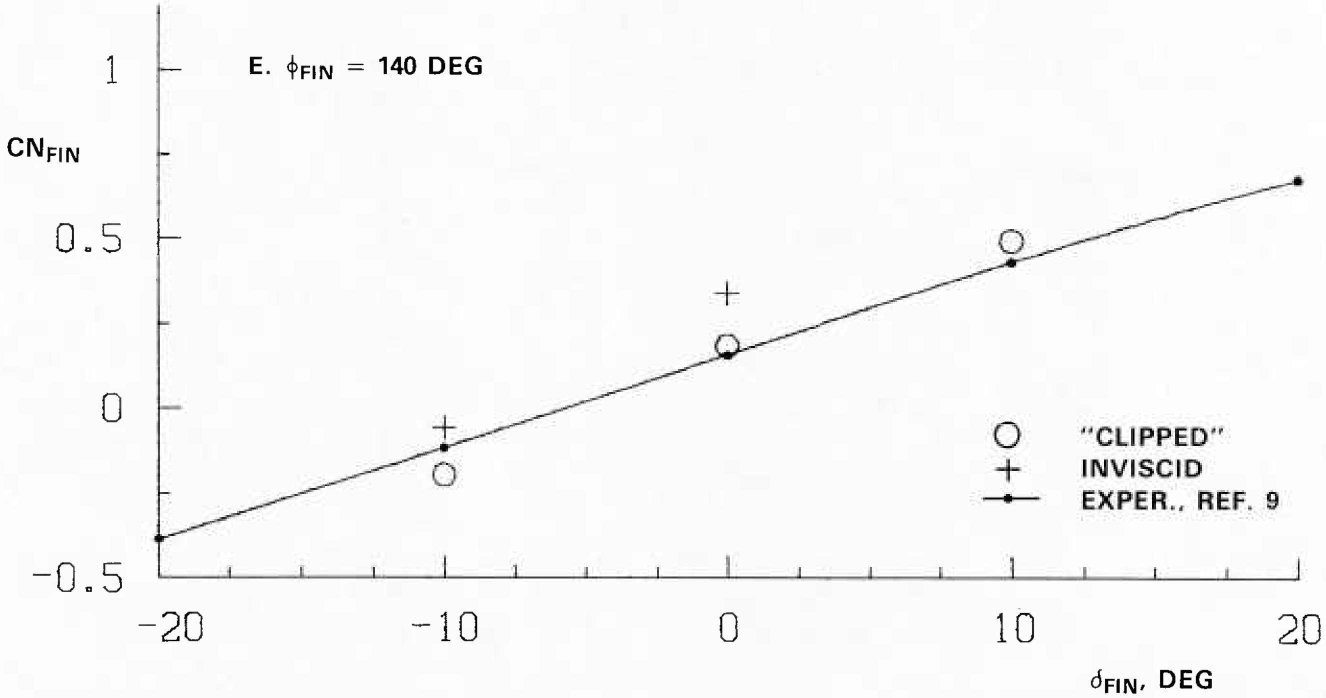

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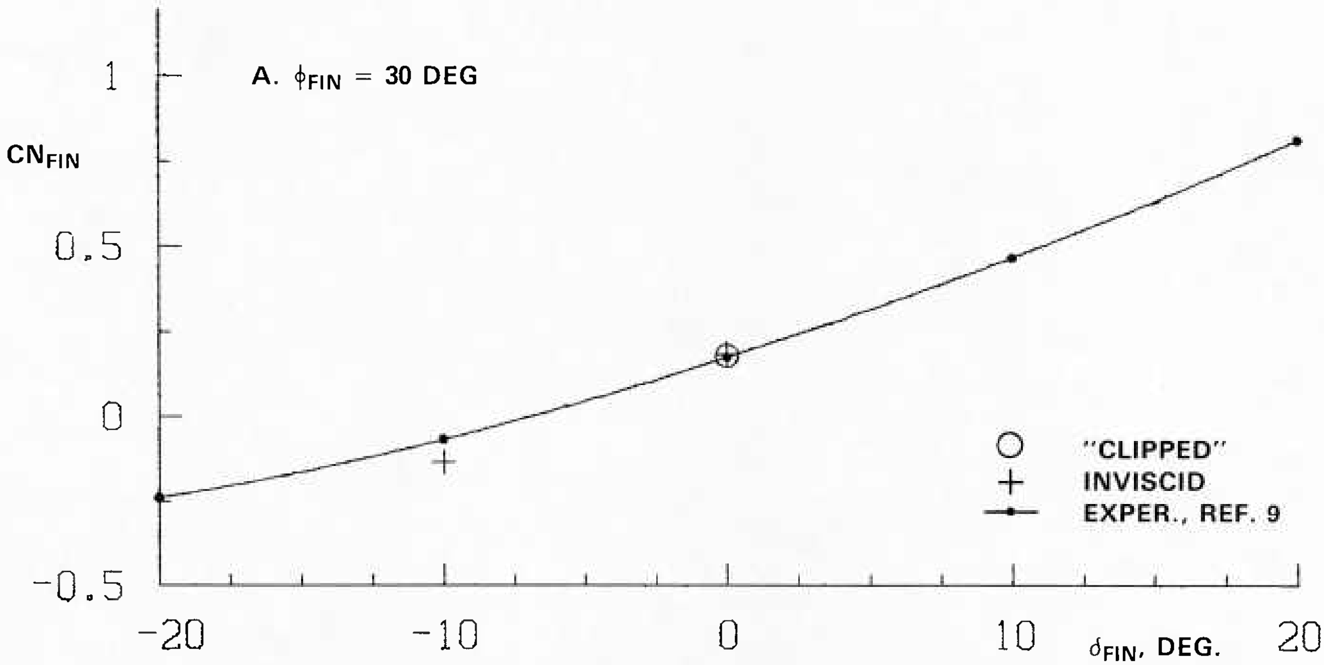
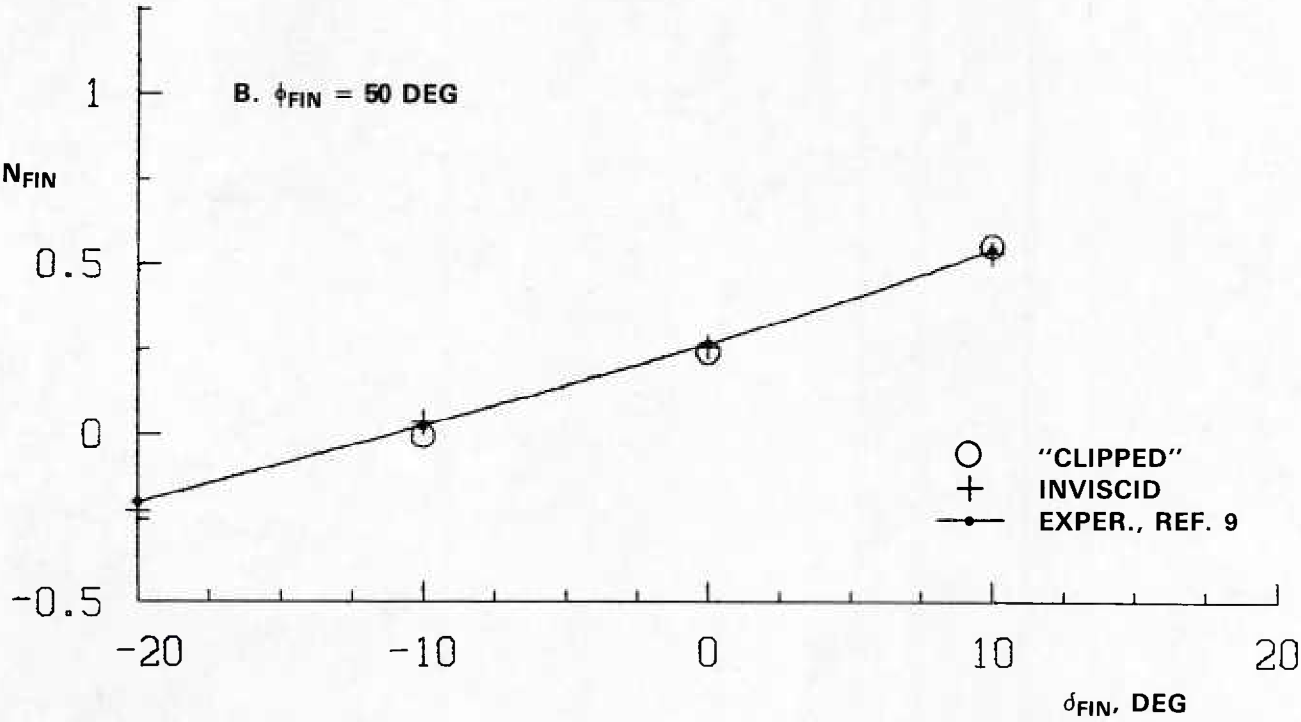
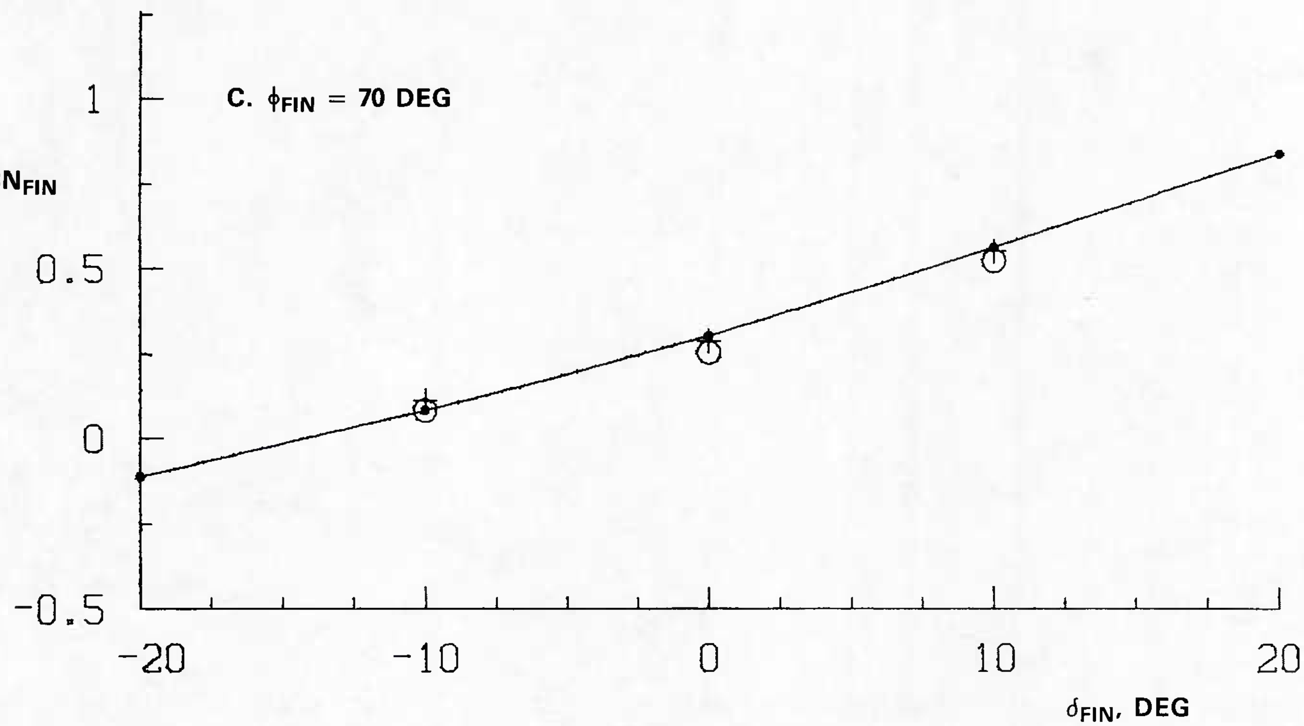


FIGURE 10. COMPARISON OF FIN NORMAL FORCE COEFFICIENT AT $M_\infty = 3$, $\alpha = 10$ DEG (MODEL GEOMETRY AS SHOWN IN FIG. 6)





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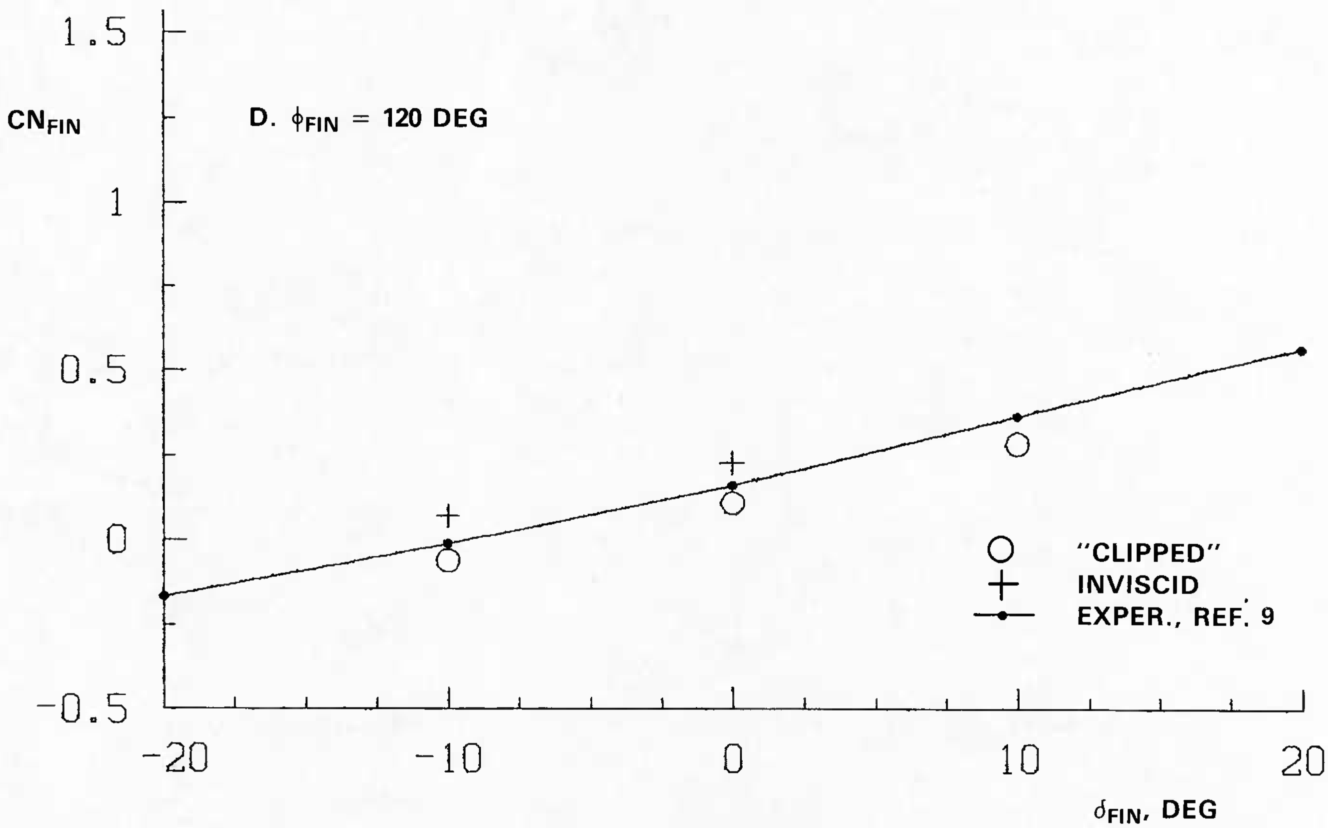

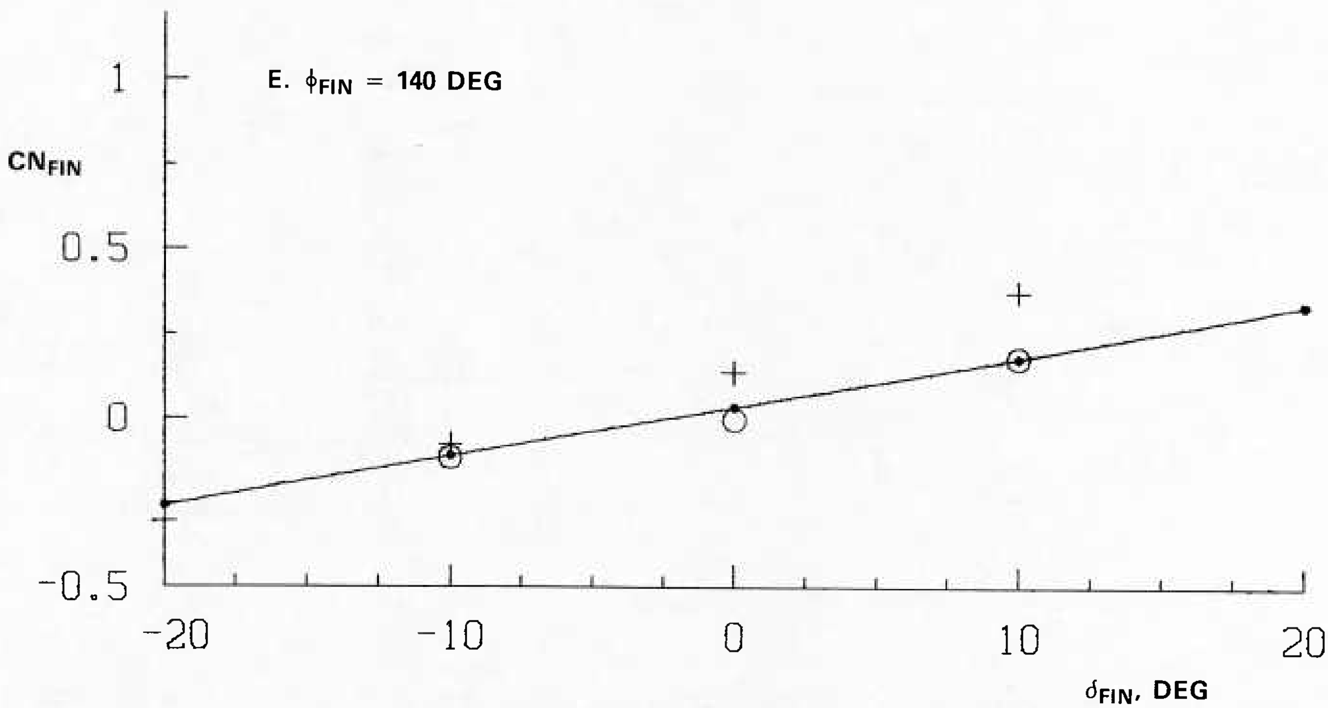

FIGURE 10. (CONTINUED)

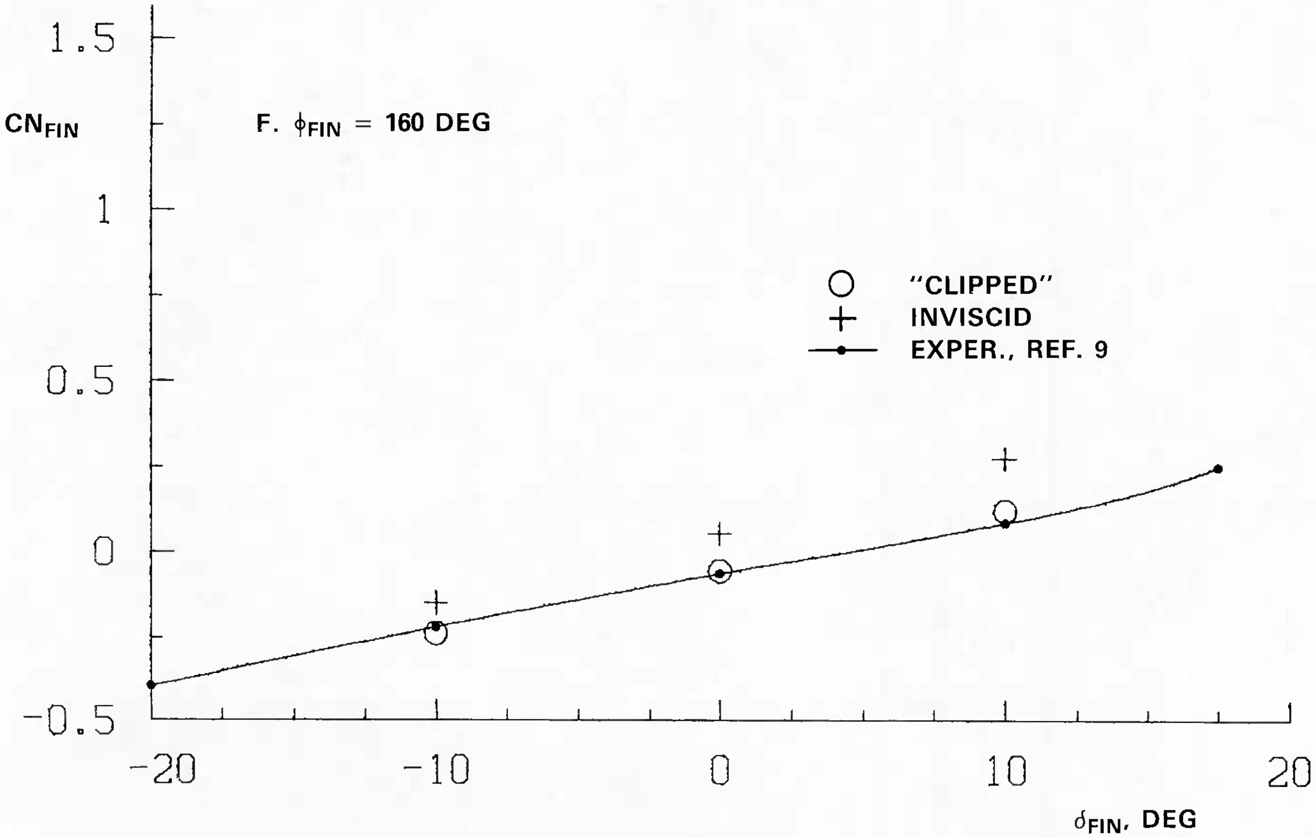

FIGURE 10. (CONCLUDED)

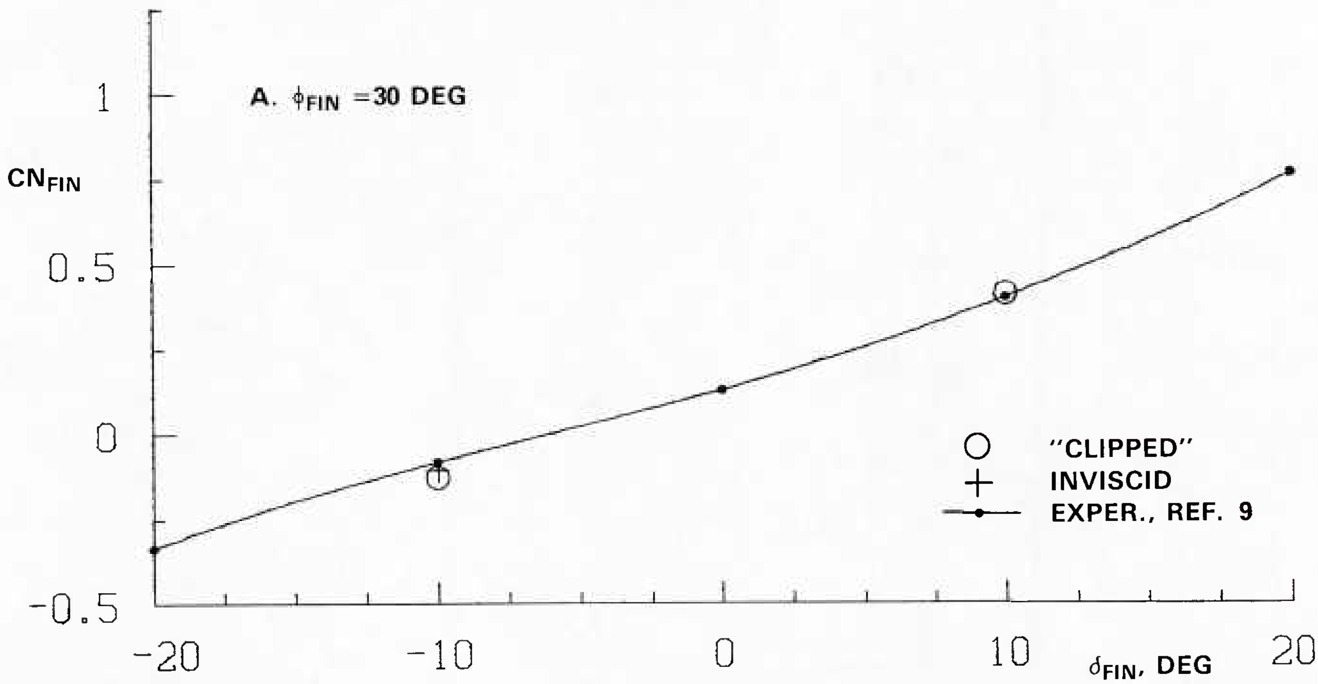

FIGURE 11. COMPARISON OF FIN NORMAL FORCE COEFFICIENT AT M_∞ = 4.5, α = 10 DEG (MODEL GEOMETRY AS SHOWN IN FIG. 6)

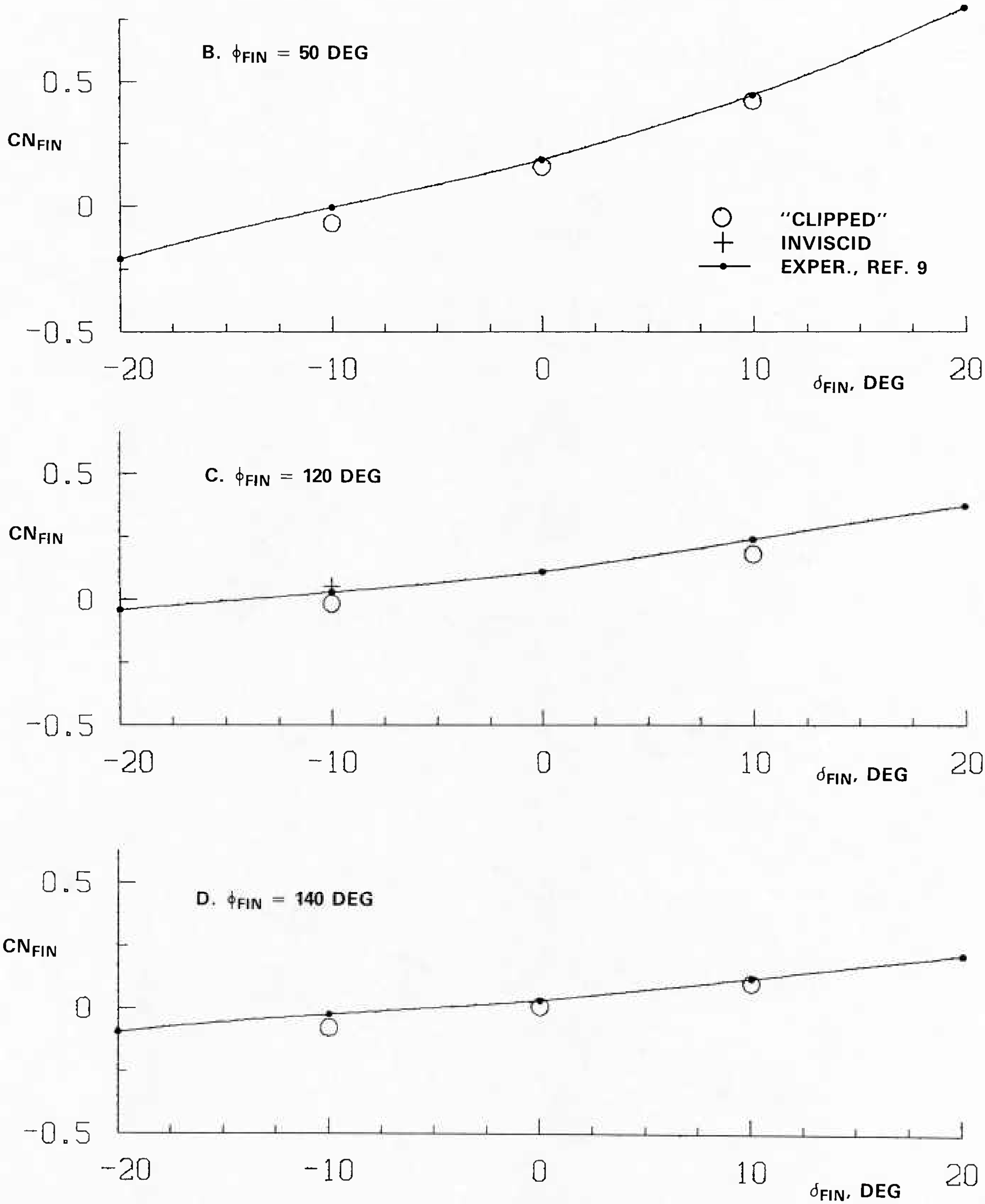

FIGURE 11. (CONCLUDED)

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APPENDIX

Update Inputs for SWINT

```
*IDENT CLIP
*I DECODE .60
C     INPUT BODY ANGLE OF ATTACK (DEG) AND Z DISTANCE AT WHICH TO START
C     CLIPPING
      ATTACK=
      ZNCL=
C
      CC1=.145*SQRT(ATTACK)
      CC2=1.0
      XW=CC1*CC2
      IF (Z.LT.ZNCL) GOTO 1314
      CV(3,1,M)=SIGN(AMIN1(SQRT(ASQ(1,M))*XW
     1   ,ABS(CV(3,1,M))),CV(3,1,M))
      U3=CV(3,1,M)
 1314 CONTINUE
*I DECODE.173
      IF (Z.LT.ZNCL) GOTO 39
      XRC=.25
      XRS=B(M)+XRC*(C(M)-B(M))
      IF (R(N,M).GT.XRS) GOTO 39
      CC2=(R(N,M)/B(M))**3
      XW=CC1*CC2
      VUR=VNM/UNM
      VK=AMIN1(ASQ(N,M)*XW*XW,VK)
C     NEW VELOCITY COMPONENTS AND CVS
      UNM=SIGN(SQRT(VK/(1.+VUR*VUR)),UNM)
      VNM=UNM*VUR
      CV(3,N,M)=UNM*U1
      CV(4,N,M)=VNM*U1
   39 CONTINUE
```

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